AD-A117 974 NAVAL RESEARCH LAB WASHINGTON DC F/G 11/6
EVALUATION OF IAEA COORDINATED PROGRAM STEELS AND WELDS FOR 288--ETC(U)
FEB 82 J R HAWTHORNE NRC-FIN-B5528
UNCLASSIFIED NRL-MR-4655 NUREG-CR-2487 NL

1 OF 1
AD
A117974

END
DATE
FILMED
09-82
DTIC

AD A117974

NUREG/CR-2487
NRL Memo Rpt 4655

# Evaluation of IAEA Coordinated Program Steels and Welds for 288 °C Radiation Embrittlement Resistance

Prepared by J. R. Hawthorne

Naval Research Laboratory

Prepared for
U.S. Nuclear Regulatory
Commission



NUREG/CR-2487 EVALUATION OF IAEA COORDINATED PROGRAM STEELS AND WELDS FOR 288 °C RADIATION EMBRITTLEMENT RESISTANCE FEBRUARY 1982

Available from

GPO Sales Program
Division of Technical Information and Document Control
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Printed copy price: $3.00

and

National Technical Information Service
Springfield, Virginia 22161

②

NUREG/CR-2487
NRL Memo Rpt 4655
R5

# Evaluation of IAEA Coordinated Program Steels and Welds for 288 °C Radiation Embrittlement Resistance

Manuscript Completed: December 1981
Date Published: February 1982

Prepared by
J. R. Hawthorne

Naval Research Laboratory
Washington, D. C. 20375

**Prepared for**
**Division of Engineering Technology**
**Office of Nuclear Regulatory Research**
**U.S. Nuclear Regulatory Commission**
**Washington, D.C. 20555**
**NRC FIN B5528**

# Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555

2. The NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
   Washington, DC 20555

3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the NRC/GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations,* and *Nuclear Regulatory Commission Issuances.*

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

## ABSTRACT

Eight steel materials supplied by the Federal Republic of Germany, France and Japan to the International Atomic Energy Agency (IAEA) Program on "Analysis of the Behavior of Advanced Reactor Pressure Vessel Steels Under Neutron Irradiation" were irradiated at 288°C for assessments of relative notch ductility and dynamic fracture toughness change with $\sim 2 \times 10^{19}$ n/cm$^2$, E >1 MeV. Notch ductility and fracture toughness were determined, respectively, by Charpy-V and fatigue precracked Charpy-V test methods. An A533-B steel plate (HSST 03) produced in the USA was included in the irradiation test series for reference.

The materials (plate, weld, forging) were found to be generally more resistant to radiation-induced embrittlement than the reference material. Observed dissimilarities in radiation sensitivity are attributed to copper content differences between the eight materials (0.01 to 0.07 percent copper range) and the reference plate (0.12 percent copper). Radiation resistances, however, correspond well with the trend of radiation resistance reported for USA-produced steels and welds having similar copper and phosphorus contents.

A general correlation of transition temperature elevations measured independently by the Charpy-V and the precracked Charpy-V test methods was observed.

CONTENTS

LIST OF FIGURES

## LIST OF TABLES

## PREFACE

The intent of this study was to increase knowledge on the metallurgical requirements for radiation resistant steels and, concurrently, to assess the adequacy of new specifications by the American Society for Testing and Materials and the American Welding Society for producing radiation resistant steels and welds overseas. Specific goals were to determine and compare the irradiation performance of low copper content plates, forgings, and welds produced by the Federal Republic of Germany, France, and Japan against the performance of USA-improved steel production. Results of the study are of significant value to applications of NRC Regulatory Guide 1.99 to foreign steels now used or contemplated for USA reactor vessels.

EVALUATION OF IAEA COORDINATED PROGRAM STEELS AND WELDS FOR 288°C RADIATION EMBRITTLEMENT RESISTANCE

## INTRODUCTION

The International Working Group on Reliability of Reactor Pressure Components (IWG-RRPC), sponsored by the International Atomic Energy Agency (IAEA), is embarked on a coordinated study of the radiation embrittlement behavior of pressure vessel steels [1]. One primary goal is to assess the radiation behavior of impr[illegible]d steels produced in various countries. The intent is to demonstrate that: (a) a ca[illegible]l specification of reactor steels can eliminate the problem of potential steel failure [illegible] to neutron irradiation effects, and (b) knowledge has advanced to the point where [illegible] manufacture and welding technology can routinely produce steel vessels of [illegible] radiation resistance. The IWG-RRPC study currently encompasses plates, forgings and welds produced by the Federal Republic of Germany (FRG), France and Japan and includes a reference steel plate produced in the United States.

The Naval Research Laboratory (NRL), with the support of the U. S. Nuclear Regulatory Commission (NRC), joined the IWG-RRPC effort at its conception (October 1977) in the interest of furthering knowledge on the metallurgical requirements for radiation resistant steels. Current technology for improved steels stems largely from earlier NRL research [2-5]. Specific NRL-NRC interests include the determination of irradiation characteristics of overseas steel production, the relative radiation resistance of USA versus non-USA steel production, and, the correlation of Charpy-V notch ductility and fracture toughness property changes produced by irradiation. Anticipated results were expected to be of significant value to the NRC Regulatory Guide 1.99 [6] for application to foreign steels in USA vessels and to construction codes.

## APPROACH

Determinations of radiation resistance reported here center on preirradiation versus postirradiation notch ductility and dynamic fracture toughness assessments. Notch ductility tests employed the standard ASTM Charpy-V ($C_V$) specimen, Type A [7]. Fracture toughness ($K_J$) tests employed a fatigue precracked Charpy-V ($PCC_V$) specimen and J-integral assessment procedures. $K_J$ values were based on energy absorbed to maximum load corrected for specimen and test machine compliance. The

test procedure, developed by the Electric Power Research Institute (EPRI), is described in Ref. 8. It will be noted that J-integral values based on maximum load imply an absence of stable (rising load) crack extension; thus, the reported values for upper shelf temperatures may overestimate the $K_J$ at crack initiation for the relatively high toughness materials investigated.

Material irradiations were conducted in the State University of New York at Buffalo 2MW pool reactor (UBR) at 288°C, comparable to reactor vessel operating temperatures. Typically, the $C_v$ and $PCC_v$ specimens of an individual material were commingled in the irradiation asssembly to provide an exact match of neutron fluence and exposure temperature histories.

## MATERIALS

Nine materials produced commercially were evaluated with irradiation. The materials are identified by their source, composition and heat treatment condition in Table 1. Table 2 indicates the orientation and location of the specimens in the source material. Preirradiation tensile properties as determined by NRL are listed in Table 3.

Fatigue precracking of the $PCC_v$ specimens was accomplished prior to irradiation. The nominal crack length to specimen width ratio, a/W, was 0.5. The maximum stress intensity, $K_f$, for the last 0.76 mm (0.030 in.) of fatigue crack growth was equal to or less than 22 MPa$\sqrt{\text{m}}$ (20 ksi$\sqrt{\text{in.}}$).

## IRRADIATION EXPERIMENTS

The large number of test materials necessitated the use of four irradiation assemblies. Contents of individual assemblies and neutron fluences received are indicated in Table 4. Fluences were determined from iron wire neutron dosimeters placed within each array of specimens. Neutron spectrum conditions for irradiation locations within the fuel lattice of the UBR reactor have been calculated for NRL by the Hanford Engineering Development Laboratory (HEDL) [9]. For the specific in-core positions used, the calculated spectrum fluence ($\Phi^{cs}$) and the fluence based on an assumed fission spectrum ($\Phi^{fs}$) have the relation:

$$\Phi^{cs} = 1.22\ \Phi^{fs}\ (E > 1.0\ \text{MeV}) \qquad (1)$$

Also, the HEDL calculations show that the calculated spectrum fluence for neutron energies greater than 1.0 MeV and the calculated spectrum fluence for neutron energies greater than 0.1 MeV have the relation:

Table 1. Test Materials

| Material/ Producer | Codes | Thickness (mm) | | Chemical Composition (wt.%) C | Mn | Si | P | S | Ni | Cr | Mo | Cu | Other | Heat Treatment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HSST A533-B Plate 03 (Lukens Steel) | 3 MU, 3 NE | 305 | | .20 | 1.26 | .25 | .011 | .018 | .56 | .10 | .45 | .12 | | 1 |
| Japan A533-B Plate (Nippon Steel) | 107 | 251 | | .18 | 1.48 | .22 | .007 | .007 | .66 | .20 | .57 | .01 | | 2 |
| Japan A508-3 Forging (Japan Steel) | 212, 213 | 302 | | .18 | 1.35 | .27 | .007 | .005 | .76 | .12 | .49 | .04 | | 3 |
| Japan S/A Weld (Mitsubishi) | 502, 503 | 248 | | .07 | 1.20 | .32 | .008 | .003 | .89 | .06 | .50 | .04 | | 4 |
| Japan A533-B Plate (Parent Plate for Weld 502) | LG | 245 | | (Not Available) | | | | | | | | | | |
| A533-B Class 1 (MARREL) | FP | 310 | | .23 | 1.44 | .23 | .007 | .002 | .65 | .03 | .51 | .03 | .02 Al<br>.004 Sn<br>.022 As | 6 |
| A508 Class 3 (FRAMATOME) | FF | 230 | | .15 | 1.37 | .25 | .009 | .008 | .69 | .24 | .47 | .07 | .02 Co<br><.01 V | 7 |
| S/A Weld[a] (FRAMATOME) | FW | 220 | (1) | .056 | 1.37 | .54 | .015 | .011 | .56 | .05 | .52 | .05 | .02 Co<br>.01 V | 8 |
| | | | (2) | .075 | 1.60 | .38 | .011 | .008 | .73 | .09 | .55 | .06 | .02 Co<br>.01 V | 8 |
| S/A Weld (Thyssen-Maschinenbau) | GW | 250 | | .075 | 1.48 | .16 | .011 | .009 | .93 | .02 | .62 | .03 | .013 Al<br><.01 Co<br><.01 V | 9 |

Heat Treatments:
1. 843 to 899°C - 4 hr, WQ; 649 to 677°C - 4 hr, AC; 607 to 636°C - 20 hr, FC.
2. 880°C - 8 hr, WQ; 660°C - 6 hr, AC; 620°C - 26 hr, FC
3. 870 to 900°C - 6.4 hr, WQ; 635 to 645°C - 7.8 hr, AC.
4. (PWHT) - 615°C - 26 hr, FC.
5. Not known.
6. 900°C - 7 hr, 40, WQ; 640°C - 10 hr 35, AC; 610°C -24 hr, FC at 40C/hr
7. 865/880°C - 3 hr, WQ; 630/650°C - 5 hr 30, AC; 615°C - 8 hr, AC.
8. 617°C - 8 hr, FC at 30C/hr.
9. 610°C - 20 hr, FC.

[a] (1) 2.5 mm analysis.
(2) 4.0 mm analysis.

Table 2. Specimen Location/Orientation in Test Materials

| Material | Code | Specimen Locations (Thickness Direction) | Specimen Orientation (Long Dimension) |
|---|---|---|---|
| A533-B Plate (HSST 03) | 3MU, 3NE | 3/4T (4 layers)[a] | Transverse to Rolling Direction (TL) |
| Japan A533-B Plate | JP 107 | 1/4T (4 layers) | Transverse |
| Japan A508-3 Forging | JF 212, 213 | 1/4T (4 layers) | Transverse |
| Japan S/A Weld | JW 502, 503 | Through Weld Thickness (Major Groove-6 layers) | Perpendicular to Welding Direction |
| Japan A533-B Plate | LG (JW-BP) | 1/4T, 3/4T (2 layers each) | Transverse |
| France A533-B Plate | FP | 1/4T (4 layers) | Transverse |
| France A508-3 Forging | FF | 1/4T (3 layers) | Transverse |
| France S/A Weld | FW | Through Weld Thickness (Major Groove-6 layers) | Perpendicular to Welding Direction |
| FRG S/A Weld | GW | 1/4T (2 layers) | Perpendicular to Welding Direction |

[a]Four layers spanning the quarter thickness plane

Table 3. Tensile Properties at 24°C
(NRL Determinations)

| Material | Codes | Yield Strength[a] (0.2% Offset) (MPa) | Tensile Strength (MPa) | R. A. (%) | Elongation (in 25.4 mm) (%) |
|---|---|---|---|---|---|
| Plate | 3MU, 3NE | 464 | 628 | 65.0 | 25.3 |
| Plate | JP 107 | 442 | 589 | 72.6 | 24.7 |
| Forging | JF 212, 213 | 462 | 597 | 70.7 | 26.2 |
| Weld | JW 502, 503 | 530 | 619 | 73.0 | 24.8 |
| Plate | LG (JW-BP) | 444 | 581 | 72.6 | 28.8 |
| Plate | FP | 486 | 632 | 66.7 | 25.8 |
| Forging | FF | 501 | 626 | 70.2 | 25.6 |
| Weld | FW | 508[b] | 607 | 71.1 | 24.9 |
| Weld | GW | 529 | 583 | 74.6 | 28.2 |

[a] Average of duplicate tests (6.4 mm gage diameter x 25.4 mm gage length specimens)

[b] 5.74 mm diameter x 25.4 mm gage length specimens

Table 4. Test Material Irradiations

| NRL Experiment No. | Experiment Compartment No. | Material Codes | Fluence[a] |
|---|---|---|---|
| UBR-23 | 1 | 3 MU | 2.1 |
| | 2 | JW 502 | 2.3 |
| | 3 | JF 212 | 2.0 |
| | | LG(JW-BP) | 1.9 |
| UBR-24 | 1 | JP 107 | 2.3 |
| | 2 | JF 212 | 2.5 |
| UBR-29 | 1 | FF | 2.0 |
| | 2 | FW | 2.5 |
| | 3 | FP | 2.1 |
| | | 3 MU | 2.1 |
| UBR-30 | 3 | GW | ∿1.9[b] |

[a] $\Phi^{cs}$ (x $10^{19}$ n/cm$^2$, E > 1 MeV)

[b] Preliminary estimate

$$\Phi^{cs}\ (E > 0.1\ \text{MeV}) = 2.91\ \Phi^{cs}\ (E > 1.0\ \text{MeV}) \tag{2}$$

## RESULTS

The $C_V$ notch ductility determinations for the materials produced overseas are presented in Figs. 1 through 8. Plate code LG (Fig. 4) was the base plate material used for weld code JW. $C_V$ results for the USA-produced reference plate (A533-B steel, HSST Plate 03) are illustrated in Fig. 9. Fracture toughness $K_J$ determinations for the materials are presented in Figs. 10 through 18. The results from both test methods are summarized for comparison in Tables 5 and 6. The choice of the $C_V$ 41J (30 ft-lb) and the $K_J$ 100 MPa$\sqrt{m}$ (90 ksi$\sqrt{in.}$) temperatures to index transition temperature was arbitrary. We note that the $C_V$ 41J temperature is also used as a convenient index by the NRC Regulatory Guide 1.99 and the Code of Federal Regulations (10 CFR 50) [10] for radiation effects projections and transition temperature comparisons.

The following observations were made from the data:

Materials Provided by Japan (Figs. 1-4 and 10-13)

1. The $C_V$ 41J, $C_V$ 68J and $K_J$ 100 MPa$\sqrt{m}$ temperatures of the materials are considerably lower than those of the reference plate (Figs. 9, 18) for the unirradiated condition and for the irradiated condition. The transition temperature elevations by irradiation are also smaller than those for the reference plate. Of the former, the forging showed the greatest transition temperature elevation with neutron exposure.

2. The $C_V$ 41J and $K_J$ 100 MPa$\sqrt{m}$ transition temperature elevations by irradiation are in good general agreement.

3. The upper shelf energy levels of the materials before and after irradiation are high ( >135 J, >275 MPa$\sqrt{m}$). For the most part, $C_V$ upper shelf reductions were less than 14J. The largest reductions were exhibited by the two plates; however, their preirradiation upper shelf levels were also significantly higher than those of the remaining materials.

Materials Provided by France (Figs. 5-7 and 14-16)

1. Preirradiation and postirradiation $C_V$ 41J, $C_V$ 68J and $K_J$ 100 MPa$\sqrt{m}$ temperatures are lower than those of the reference plate with one exception. For the forging, the 41J temperature is about equal to that of the reference plate. In contrast, the 100 MPa$\sqrt{m}$ temperature of the forging is lower than that of the reference plate.

Table 5. Preirradiation and Postirradiation Charpy-V Notch Ductility Properties

| Material | Fluence[a] ($\phi$ cs) | $C_v$ 41J (°C) | | | Transition Temperature $C_v$ 68J (°C) | | | $C_v$ 0.9 mm (°C) | | | Upper Shelf Energy (J) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Irrad. | Change | Initial | Irrad. | Change | Initial | Irrad. | Change | Initial | Irrad. | Change |
| HSST 03 | 2.1 | -1 | 43 | 44 | 29 | 76 | 47 | 24 | 80 | 56 | 138 | 136 | $\sim 0$ |
| JP 107 | 2.3 | -46 | -29 | 17 | -35 | -21 | 14 | -38 | -21 | 17 | $>270$ | 212 | $\geq 58$ |
| JF 212 | 2.5 | -63 | -32 | 31 | -54 | -21 | 33 | -54 | -21 | 33 | $\sim 233$ | $\sim 218$ | $\sim 15$ |
| JW 502 | 2.3 | -42 | -23 | 19 | -29 | -12 | 17 | -34 | -7 | 28 | 184 | 184 | $\sim 0$ |
| LG(JW-BP) | 1.9 | -37 | -23 | 14 | -32 | -15 | 17 | -34 | -15 | 19 | $>270$ | 228 | $\geq 37$ |
| FP | 2.1 | -18 | -4 | 14 | 7 | 24 | 17 | -1 | 18 | 19 | 165 | 165 | $\sim 0$ |
| FF | 2.0 | $\sim -1$ | -7 | (-)6 | $\sim 7$ | 2 | (-)5 | 7 | -1 | (-)8 | 200 | $\sim 197$ | $\sim 0$ |
| FW (Layers 1-3) | 2.5 | -54 | -46 | 8 | -34 | -26 | 8 | -40 | -32 | 8 | 220 | 195 | 25 |
| FW (Layers 4-6) | 2.5 | -54 | -23 | 31 | -34 | 2 | 36 | -40 | 2 | 42 | 193 | 168 | 25 |
| GW | $\sim 1.9$[b] | -62 | -34 | 28 | -51 | -23 | 28 | -57 | -26 | 31 | $>270$ | 210 | $\geq 60$ |

[a] $10^{19}$ n/cm$^2$, E 1 MeV

[b] Preliminary estimate

Table 6. Preirradiation and Postirradiation Dynamic Fracture Toughness ($K_J$) Properties ($PCC_v$ Test Method)

| Material Codes | Fluence[a] ($\Phi$ cs) | $K_{Jd}$ 100 MPa $\sqrt{m}$ (°C) Initial | Irrad. | Change | Upper Shelf (MPa $\sqrt{m}$)[b] Initial | Irrad. | Change |
|---|---|---|---|---|---|---|---|
| HSST 03 | 2.1 | 33 | 77 | 44 | 265 | 260 | ~0 |
| JP 107 | 2.3 | -1 | 16 | 17 | 335 | 335 | ~0 |
| JF 212 | 2.5 | 2 | 35 | 33 | 355 | 325 | ~0 |
| JW 502 | 2.3 | -17 | 16 | 33 | 320 | 320 | ~0 |
| LG(JW-BP) | 1.9 | -1 | 16 | 17 | 335 | 325 | ~0 |
| FP | 2.1 | 13 | 32 | 19 | 315 | 320 | ~0 |
| FF | 2.0 | 4 | 10 | 6 | 315 | 285 | ≤ 30 |
| FW (Layers 1-3) | 2.5 | -34 | -3 | 31 | 315[d] | 330 | ~0[d] |
| FW (Layers 4-6) | 2.5 | -34 | 11 | 45 | 315 | 325 | ~0 |
| GW | 1.9[c] | -34 | 2 | 36 | 330 | 295 | 35 |

[a] $10^{19}$ n/cm$^2$, E > 1 MeV

[b] Lowest value of upper shelf test data

[c] Preliminary estimate

[d] Estimated

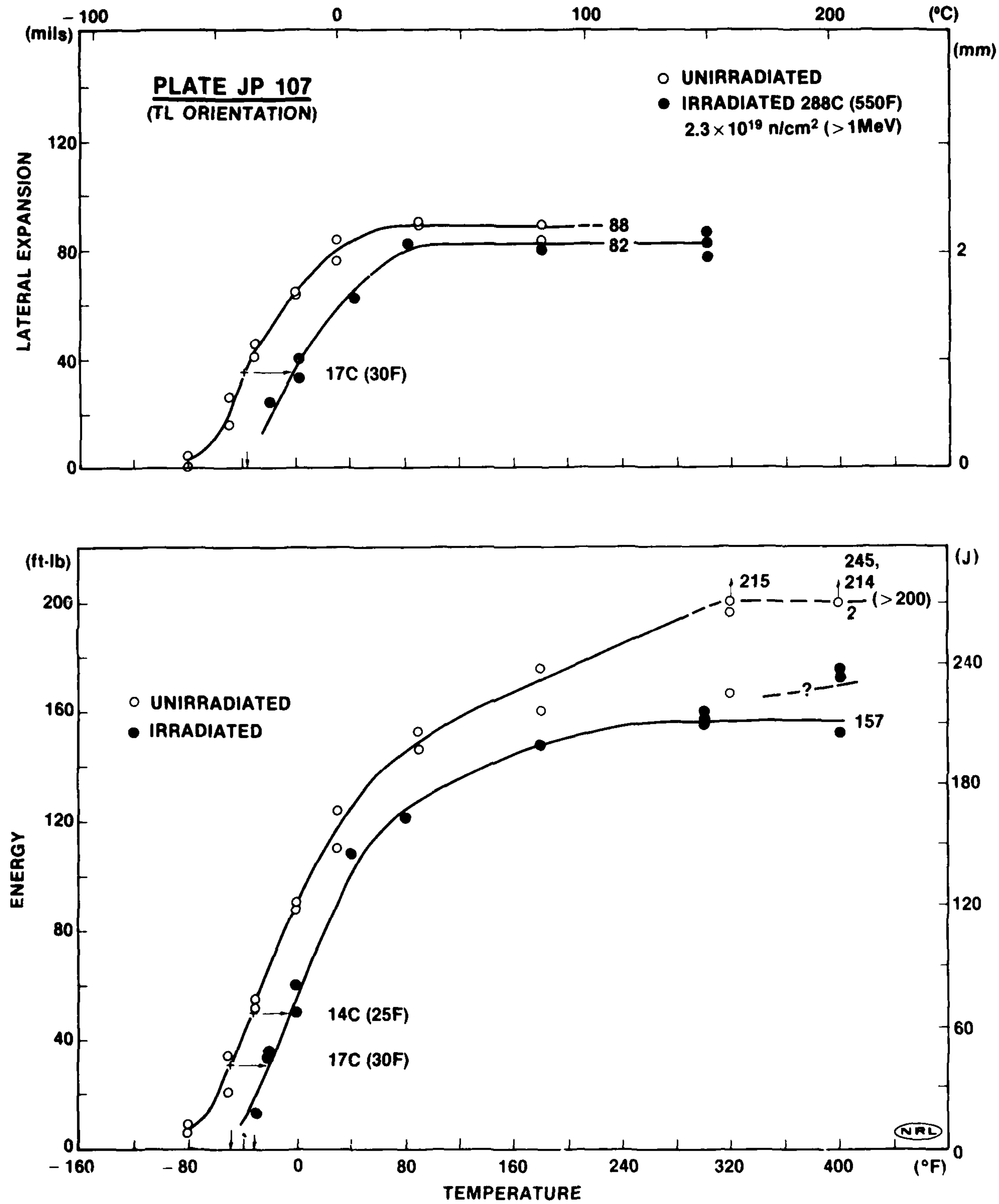


Fig. 1. Charpy-V notch ductility of the A533-B Class 1 steel plate, Code JP 107, supplied by Japan. In this Figure and in Figs. 2 through 9, the upper graph relates specimen lateral expansion and temperature while the lower graph relates specimen energy absorption and temperature.

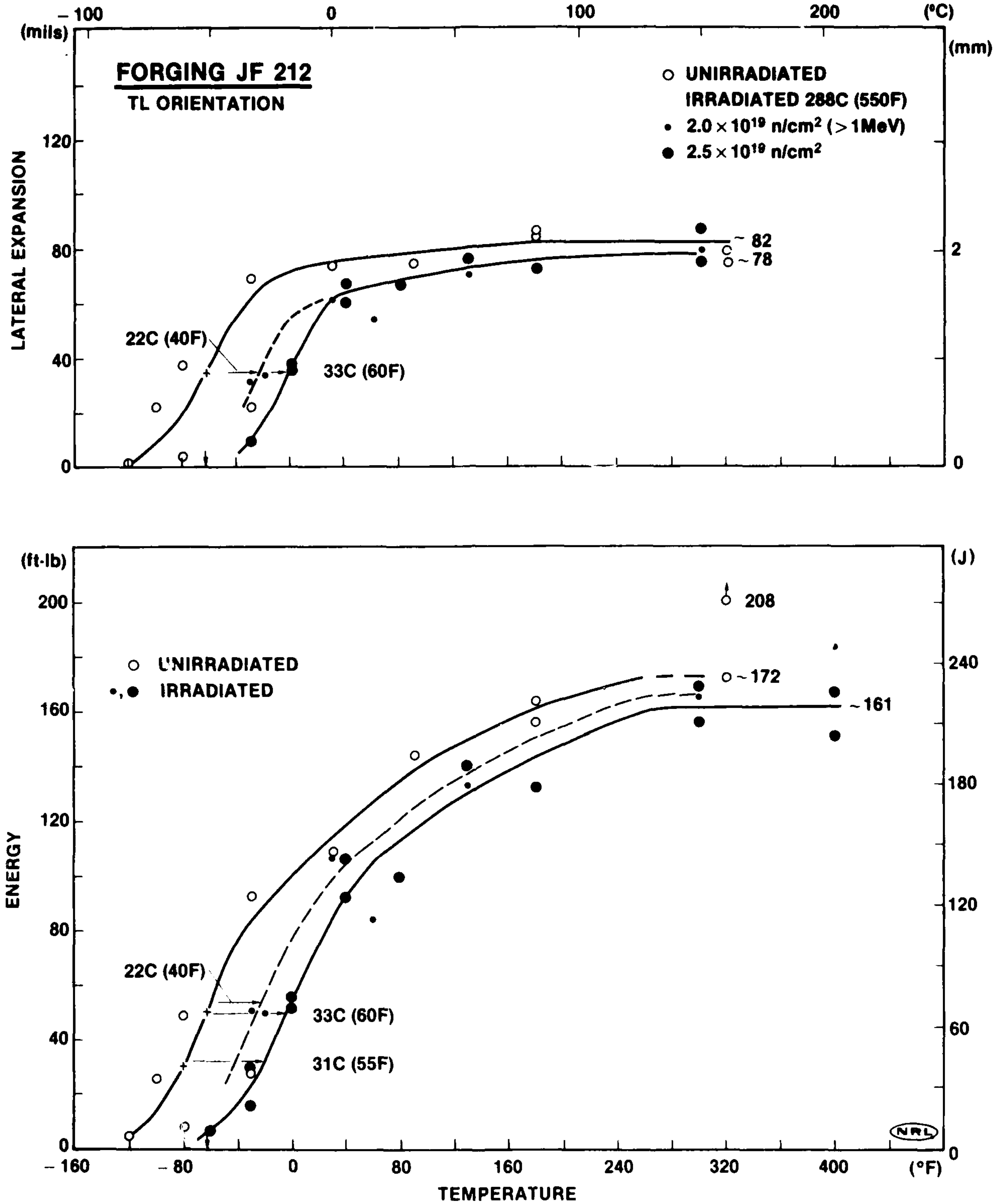


Fig. 2. Charpy-V notch ductility of the A508 Class 3 steel forging, Code JF 212, supplied by Japan.

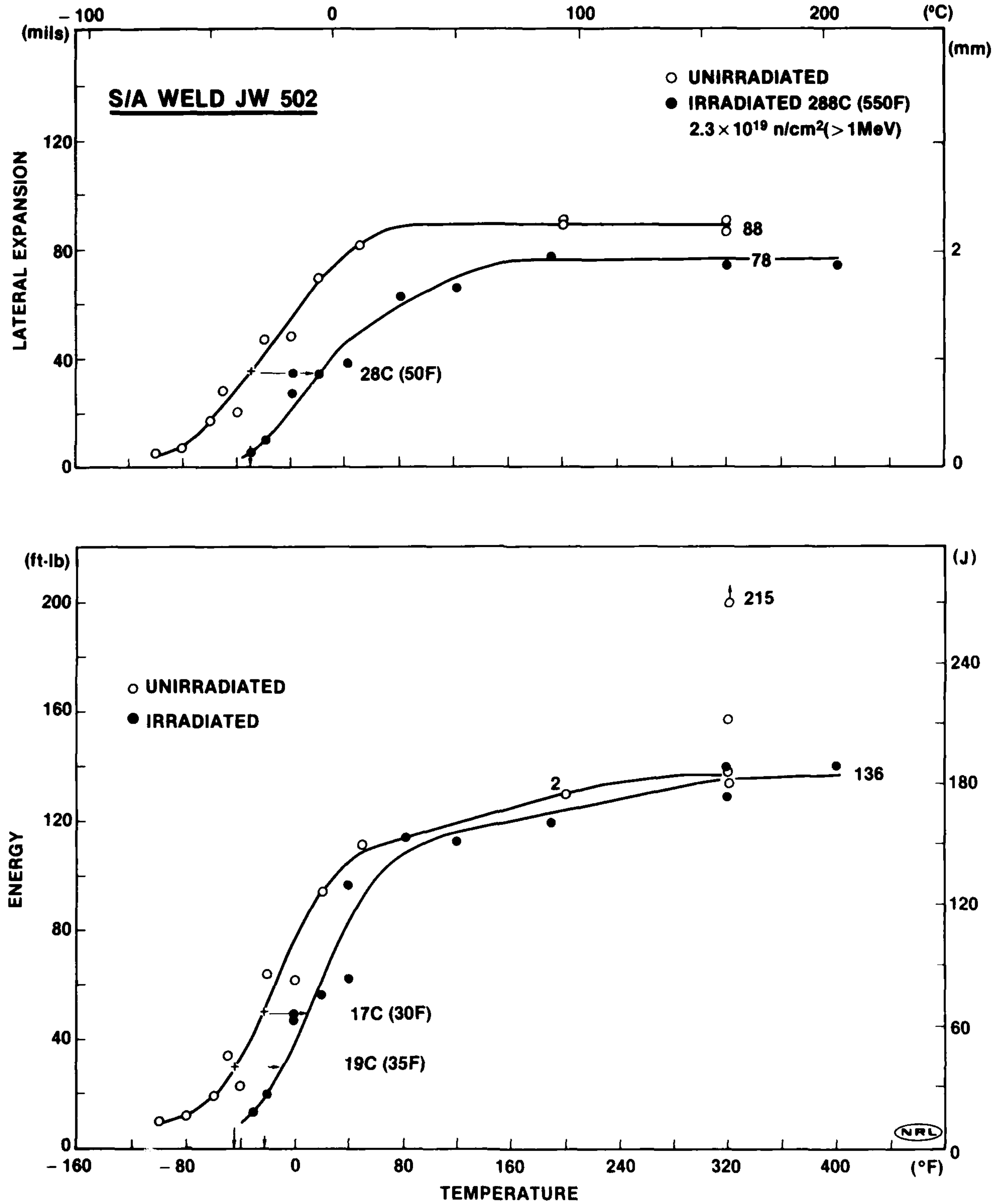


Fig. 3. Charpy-V notch ductility of the submerged arc weld, Code JW 502, supplied by Japan.

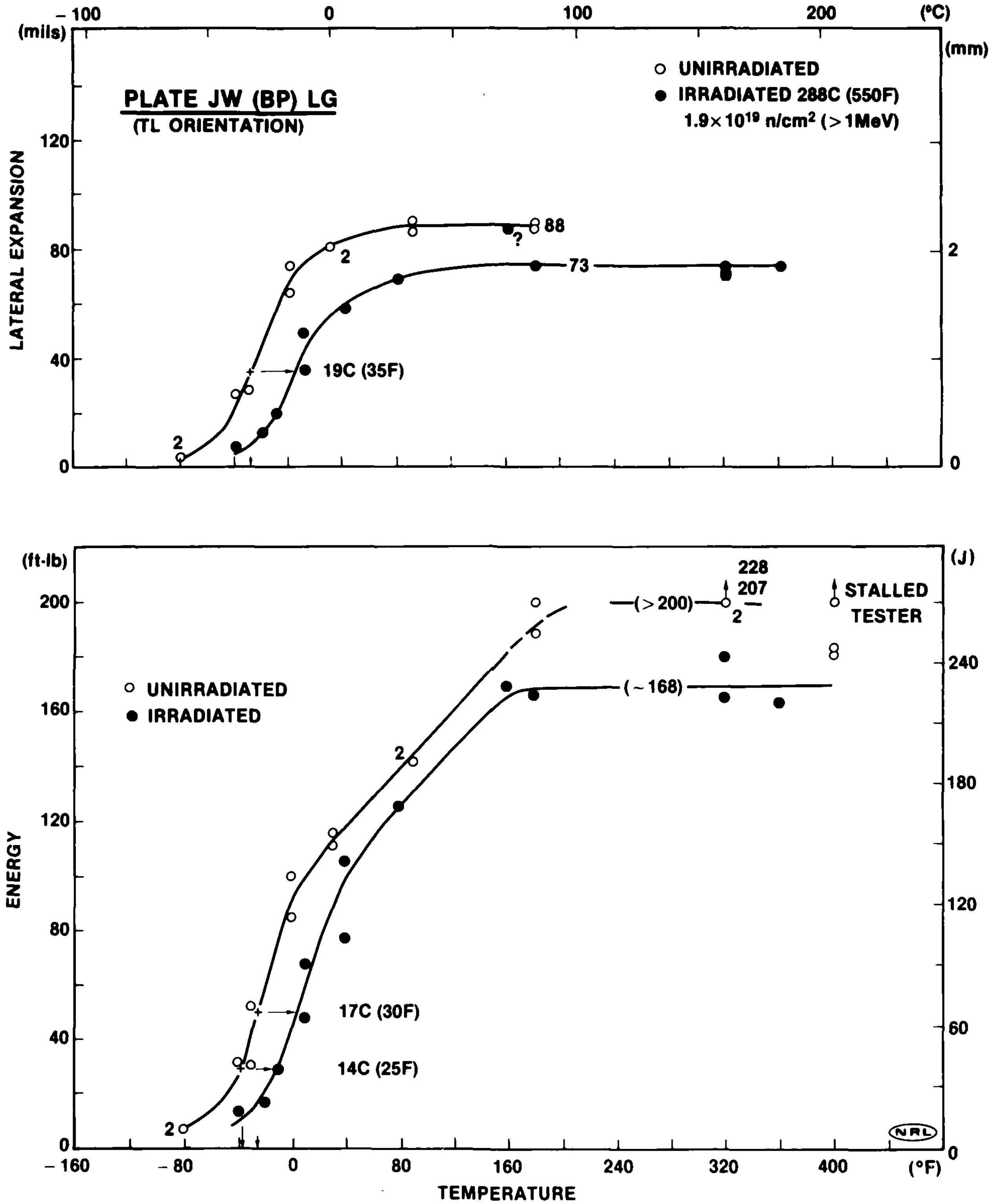


Fig. 4. Charpy-V notch ductility of the A533-B steel base plate, Code LG, for the weld Code JW 502.

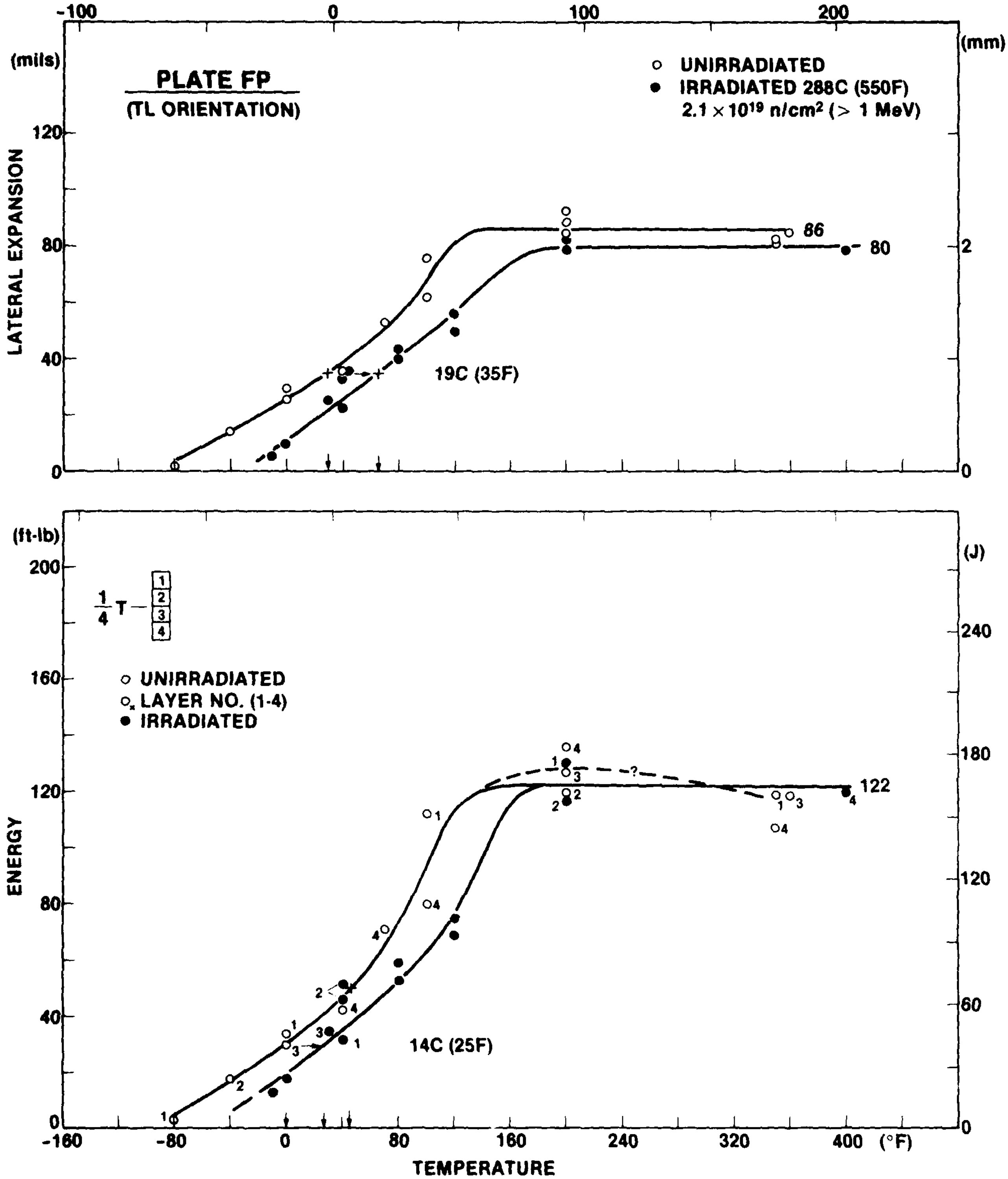


Fig. 5. Charpy-V notch ductility of the A533-B Class 1 steel plate, Code FP, supplied by France.

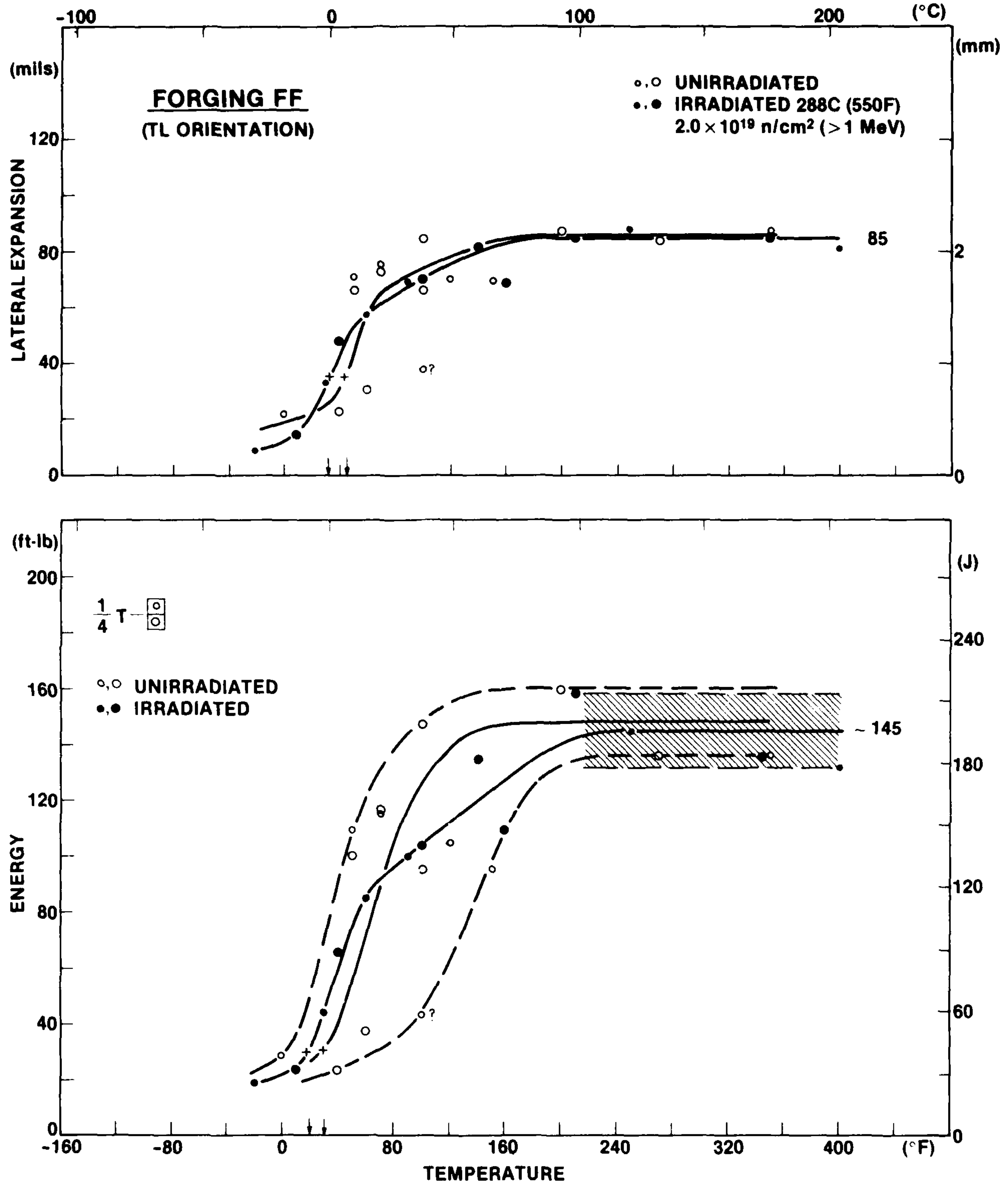


Fig. 6. Charpy-V notch ductility of the A508 Class 3 steel forging, Code FF, supplied by France.

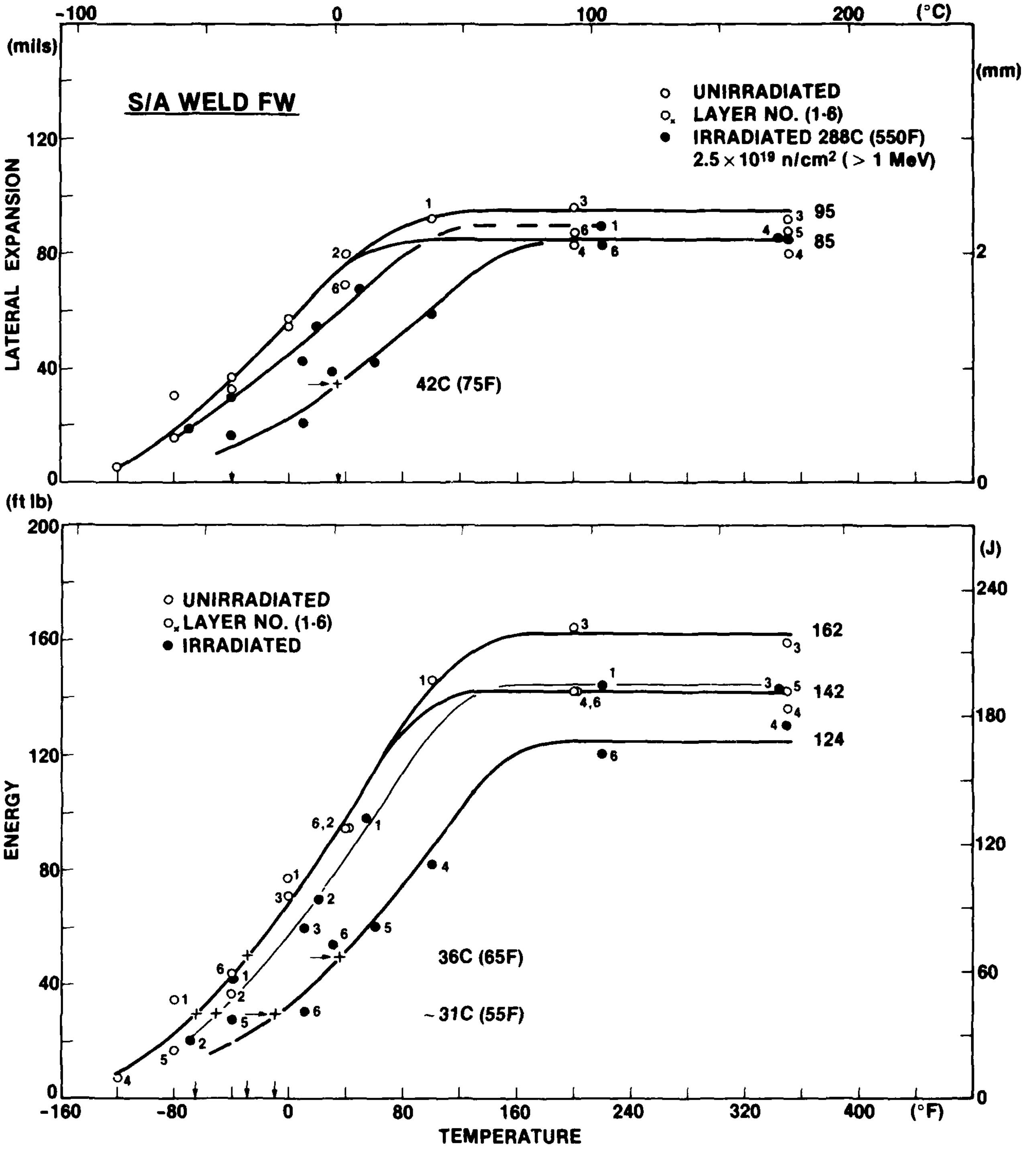


Fig. 7. Charpy-V notch ductility of the submerged arc weld, Code FW, supplied by France. Two levels of radiation embrittlement sensitivity are clearly indicated by the irradiation data, traceable to the original specimen location in the weld deposit thickness (layers 1 to 3 versus layers 4 to 6).

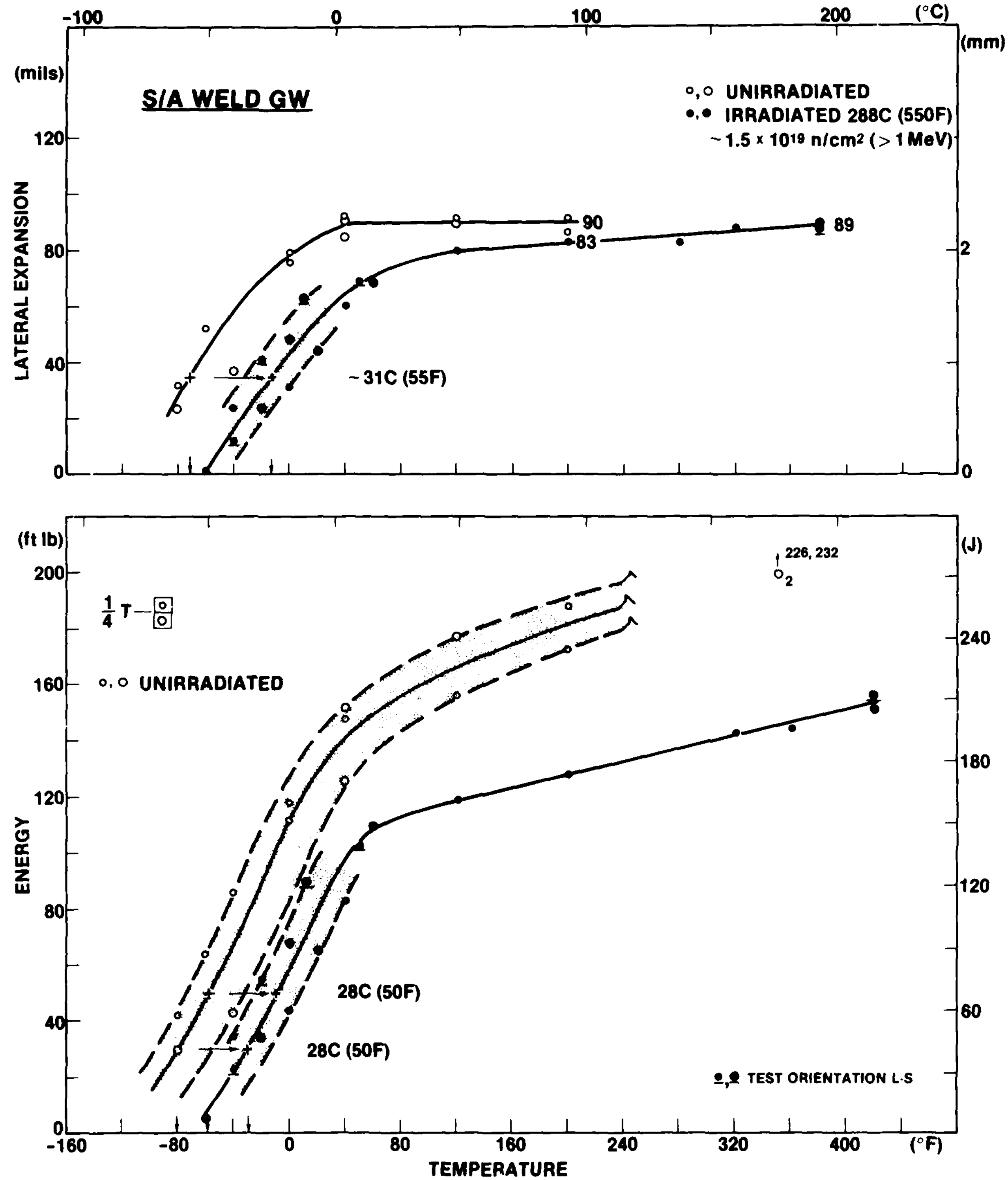


Fig. 8. Charpy-V notch ductility of the submerged arc weld, Code GW, supplied by the FRG.

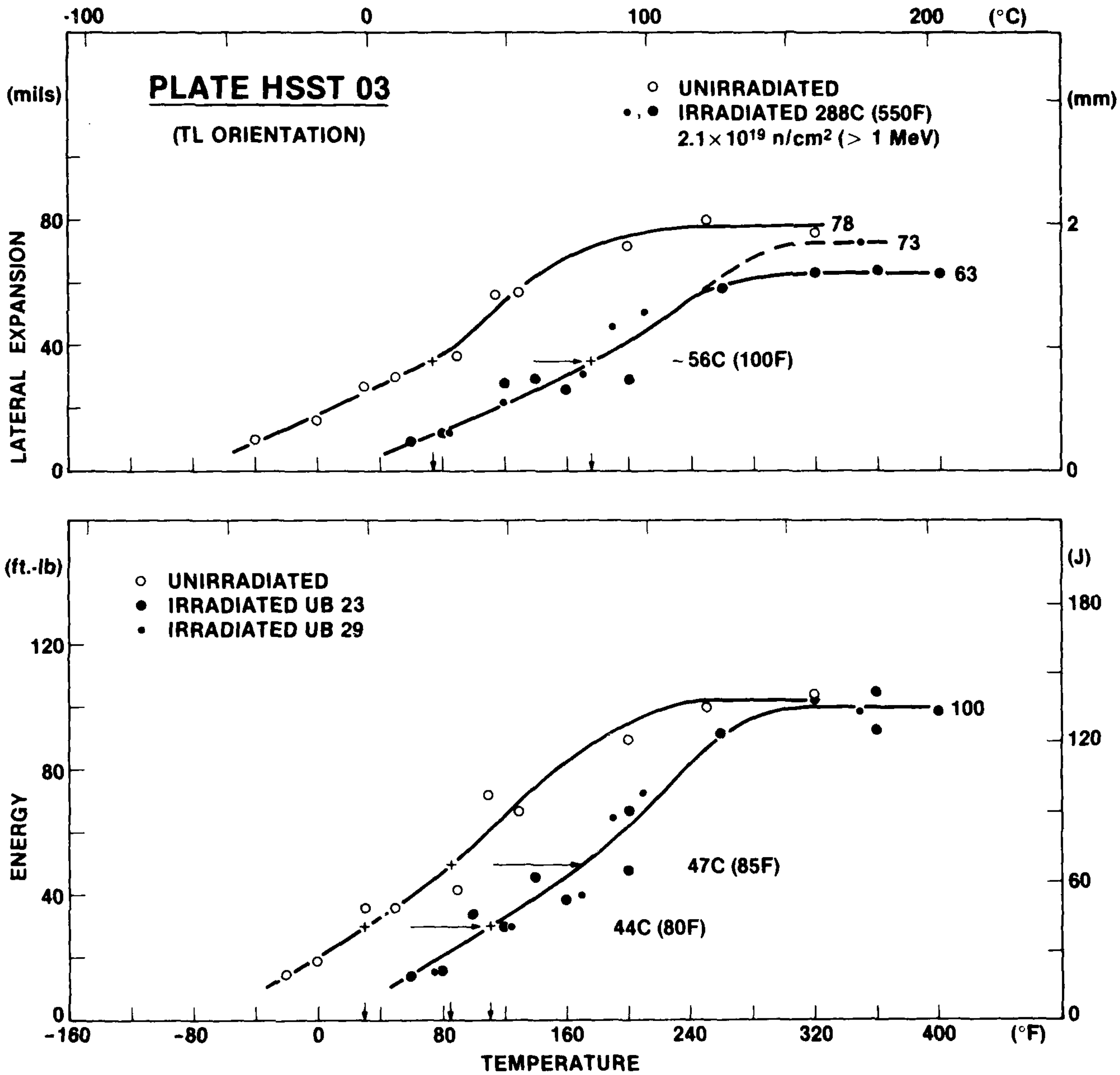


Fig. 9. Charpy-V notch ductility of the A533-B Class 1 reference plate (HSST Program Plate 03), Code 3 MU, supplied by the USA.

2. Transition temperature elevations by irradiations were much smaller than those for the reference plate with the exception of one portion of the weld.

3. Weld code FW data describe two levels of radiation resistance depending on the original specimen location in the weld. Specimens taken from thickness layers 1 to 3 indicate a higher radiation resistance than specimens taken from layers 4 to 6 in terms of 41J temperature elevation and upper shelf level. A data separation, though less pronounced, is also evident in the $K_J$ results. The observations in turn suggest that two, not one, weld wire compositions were used for filling the major groove of the weld from whence the specimens were taken.

4. Each of the materials exhibited a high upper shelf energy level after irradiation; an upper shelf reduction was observed for the weld only.

Material provided by FRG (Figs. 8 and 17)

1. Preirradiation and postirradiation $C_v$ 41J, $C_v$ 68J and $K_J$ 100 MPa$\sqrt{m}$ temperatures are significantly lower than those for the reference plate.

2. A relatively large reduction in upper shelf energy was found in postirradiation $C_v$ testing; a small reduction in upper shelf toughness was observed in postirradiation $PCC_v$ tests.

Figure 19 compares the preirradiation and postirradiation transition temperatures and transition temperature elevations of all nine materials. Material-to-material differences are noted; however, the material properties in general appear to be better than those of the USA 305 mm thick reference plate. The trend can be attributed to processing differences in combination with material thickness differences and to material dissimilarities in copper and phosphorus contents.

Transition Temperature Elevation versus Test Method

Figures 20 and 21 compare the measured $C_v$ transition temperature elevations with the $K_J$ 100 MPa $\sqrt{m}$ transition temperatures measured by the $PCC_v$ method. On balance, agreement within 15°C is observed suggesting a possible correlation which will be of benefit to reactor vessel surveillance programs. An exception to the trend is found in one data set for material code FW (layers 1-3). An explanation for the inconsistency cannot be tendered at this time. A more stringent test of the correlation would have required a greater number of irradiation specimens than those available.

Other $C_v$ versus $PCC_v$ postirradiation test comparisons are underway at NRL for NRC and EPRI sponsors [11,12].

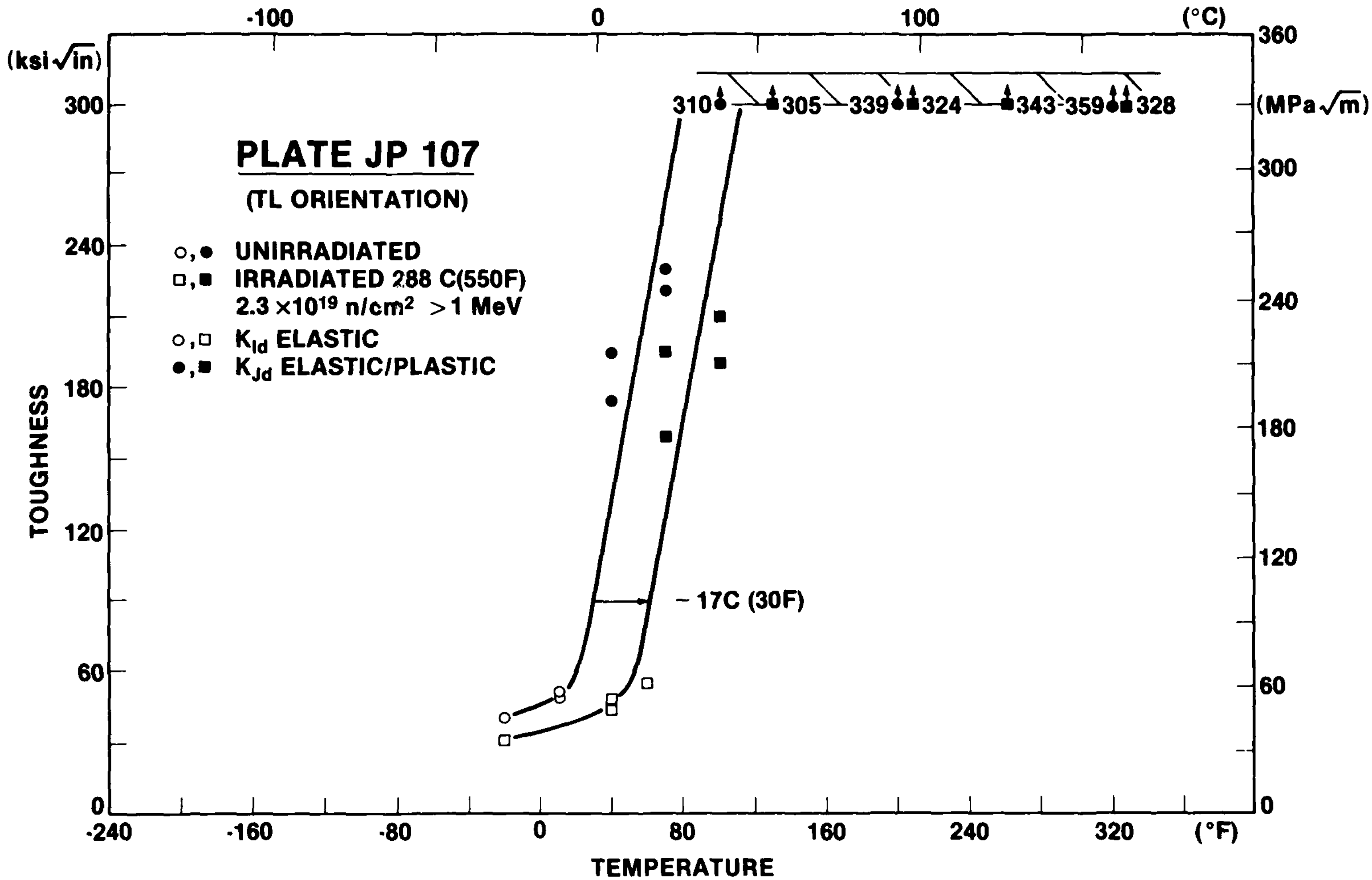


Fig. 10. Fracture toughness of the A533-B Class 1 plate, Code JP 107, supplied by Japan ($PCC_v$ Test Method)

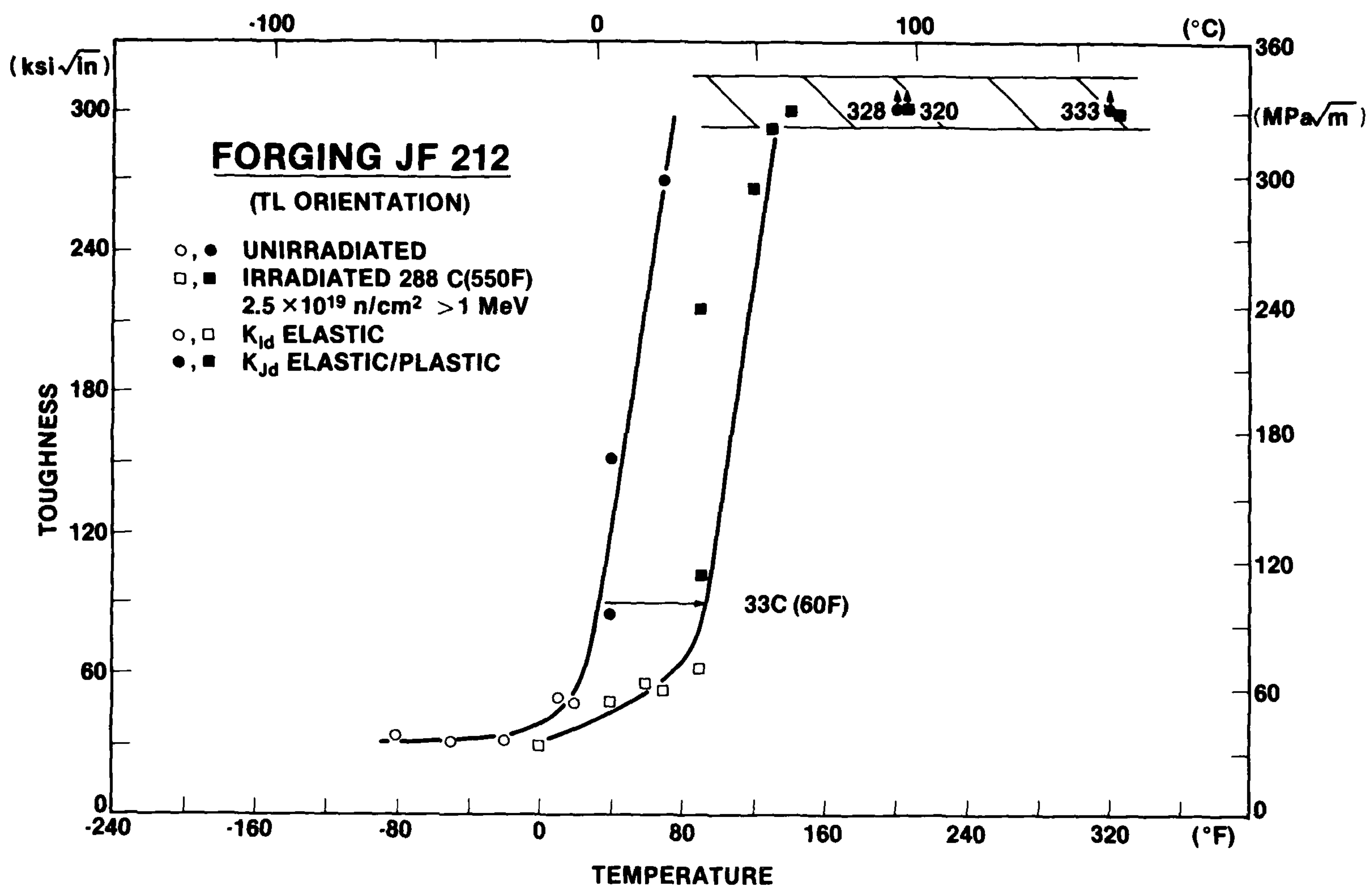


Fig. 11. Fracture toughness of the A508 Class 3 forging, Code JF 212, supplied by Japan ($PCC_v$ Test Method)

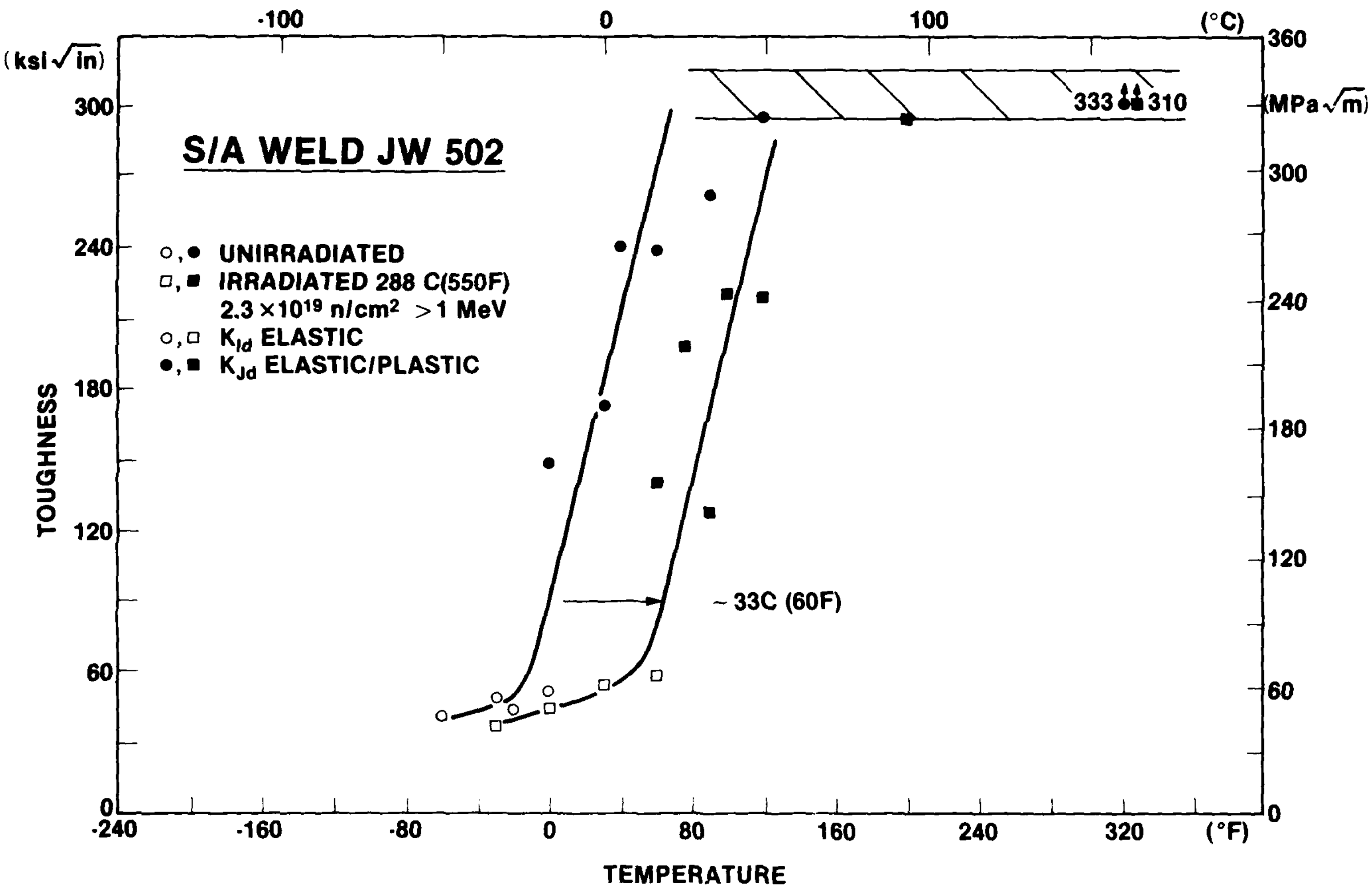


Fig. 12. Fracture toughness of the submerged arc weld, Code JW 502, supplied by Japan ($PCC_v$ Test Method)

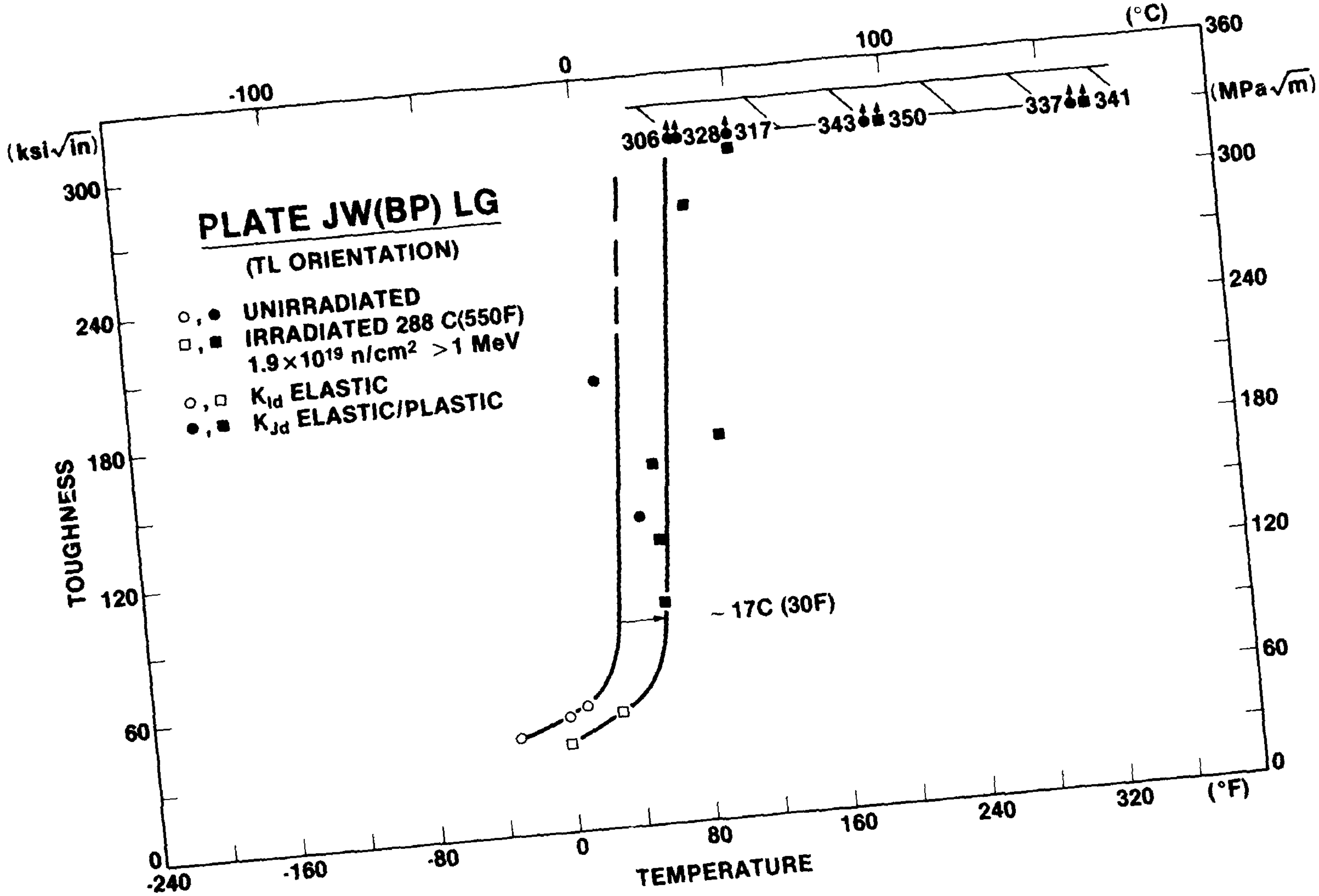


Fig. 13. Fracture toughness of the A533-B base plate, Code LG, for the weld Code JW 502 ($PCC_v$ Test Method)

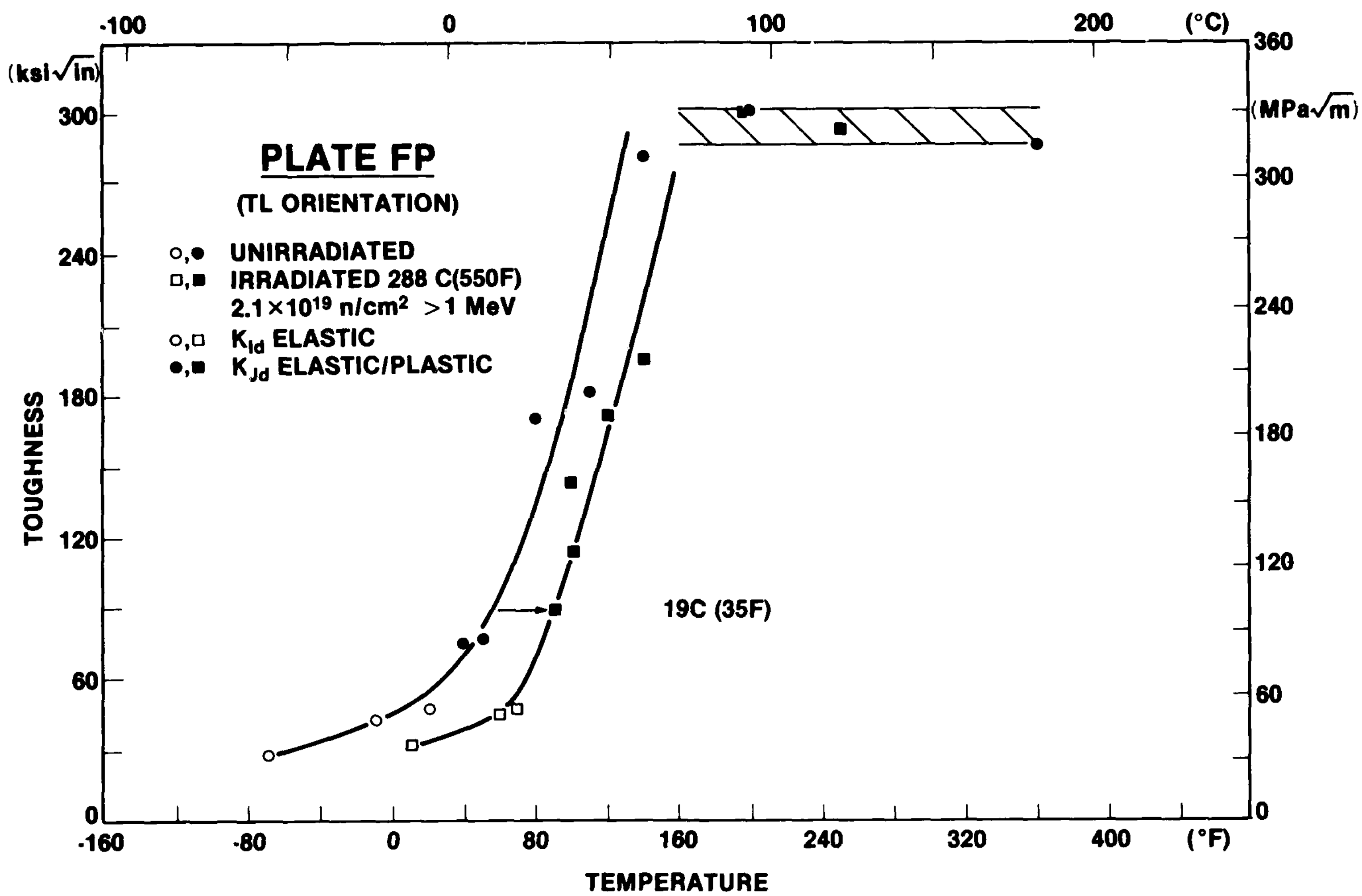


Fig. 14. Fracture toughness of the A533-B Class 1 plate, Code FP, supplied by France ($PCC_v$ Test Method)

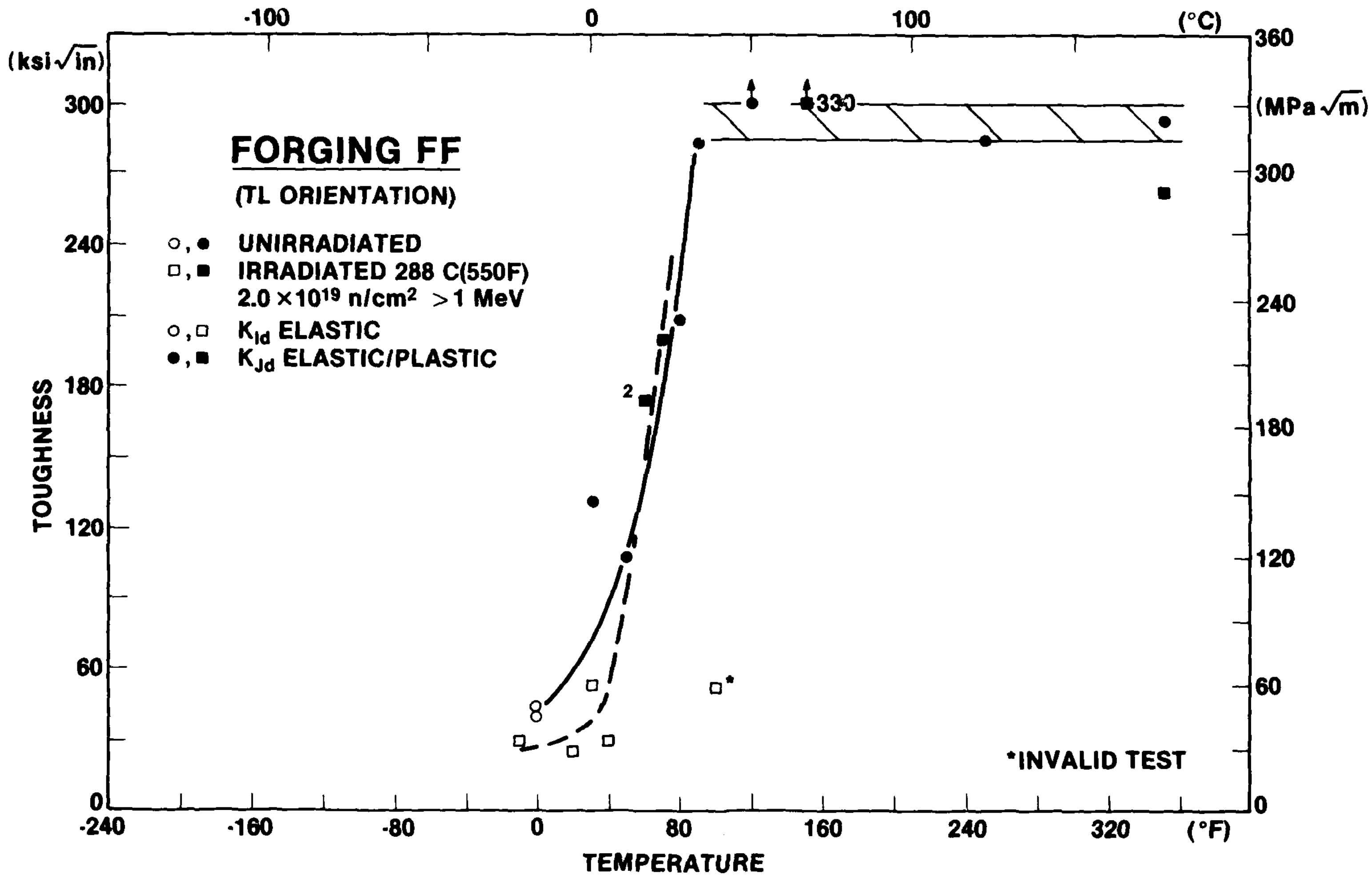


Fig. 15. Fracture toughness of the A508 Class 3 forging, Code FF, supplied by France ($PCC_v$ Test Method)

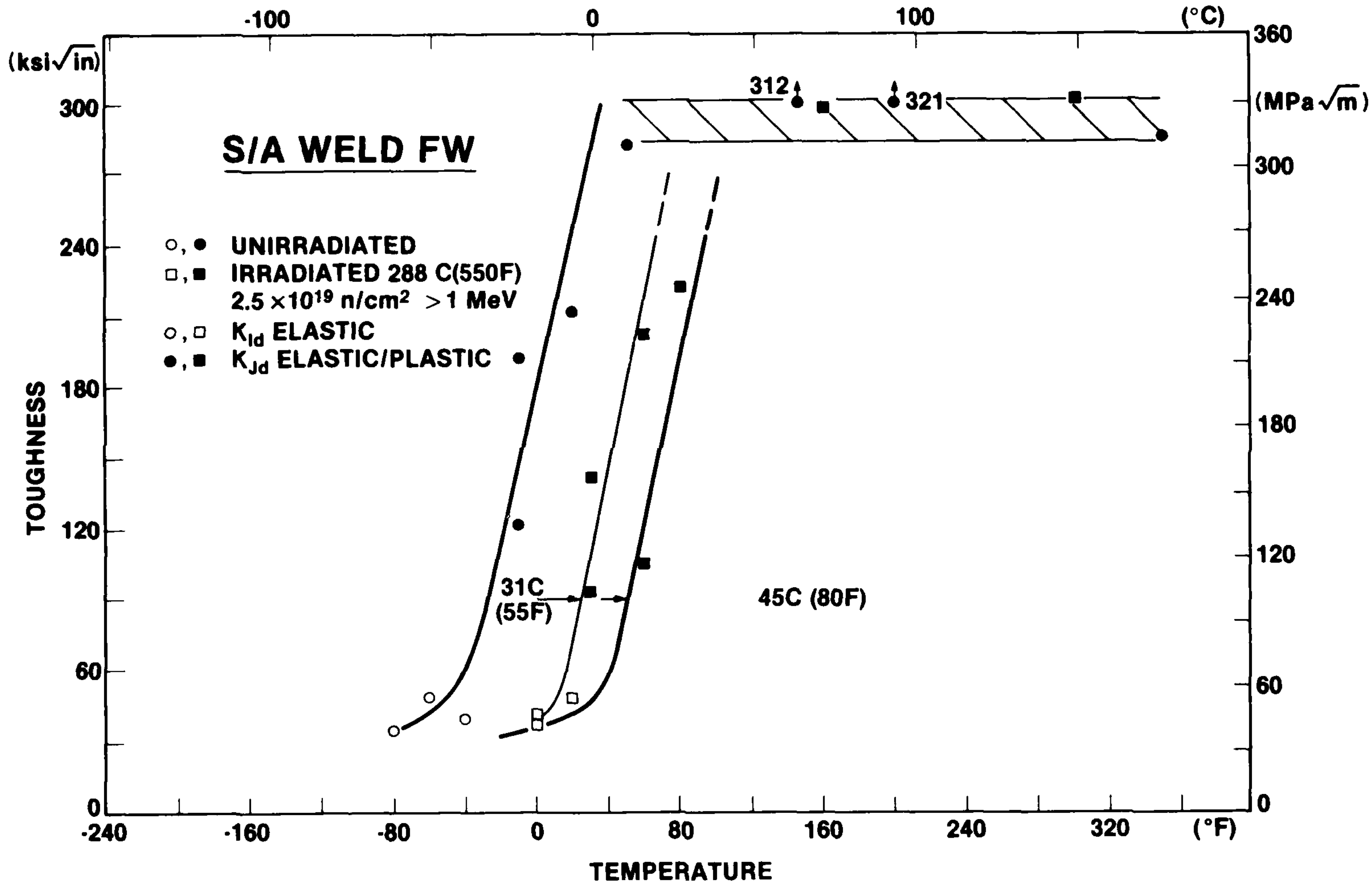


Fig. 16. Fracture toughness of the submerged arc weld, Code FW, supplied by France ($PCC_v$ Test Method)

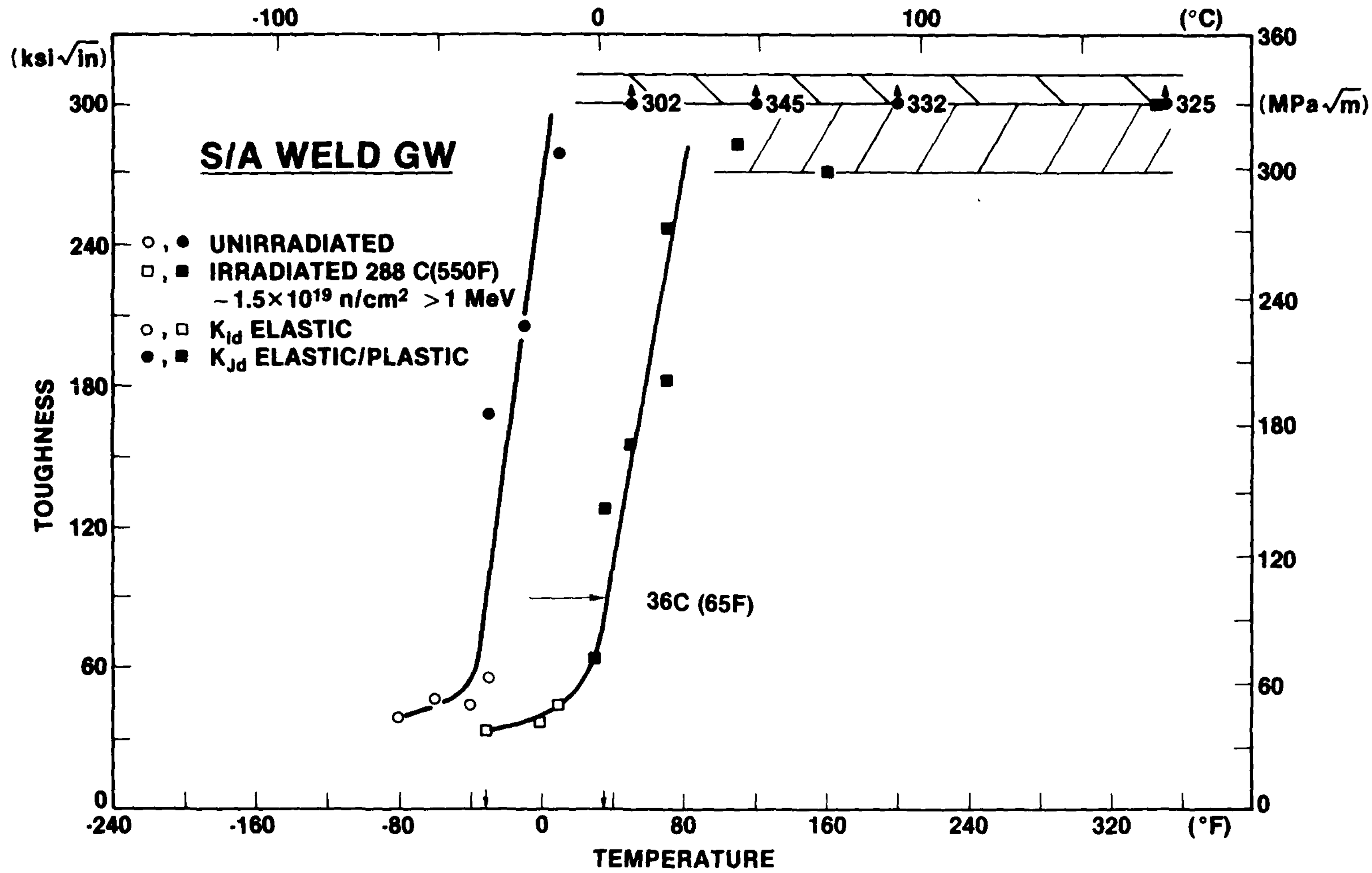


Fig. 17. Fracture toughness of the submerged arc weld, Code GW, supplied by the FRG ($PCC_v$ Test Method)

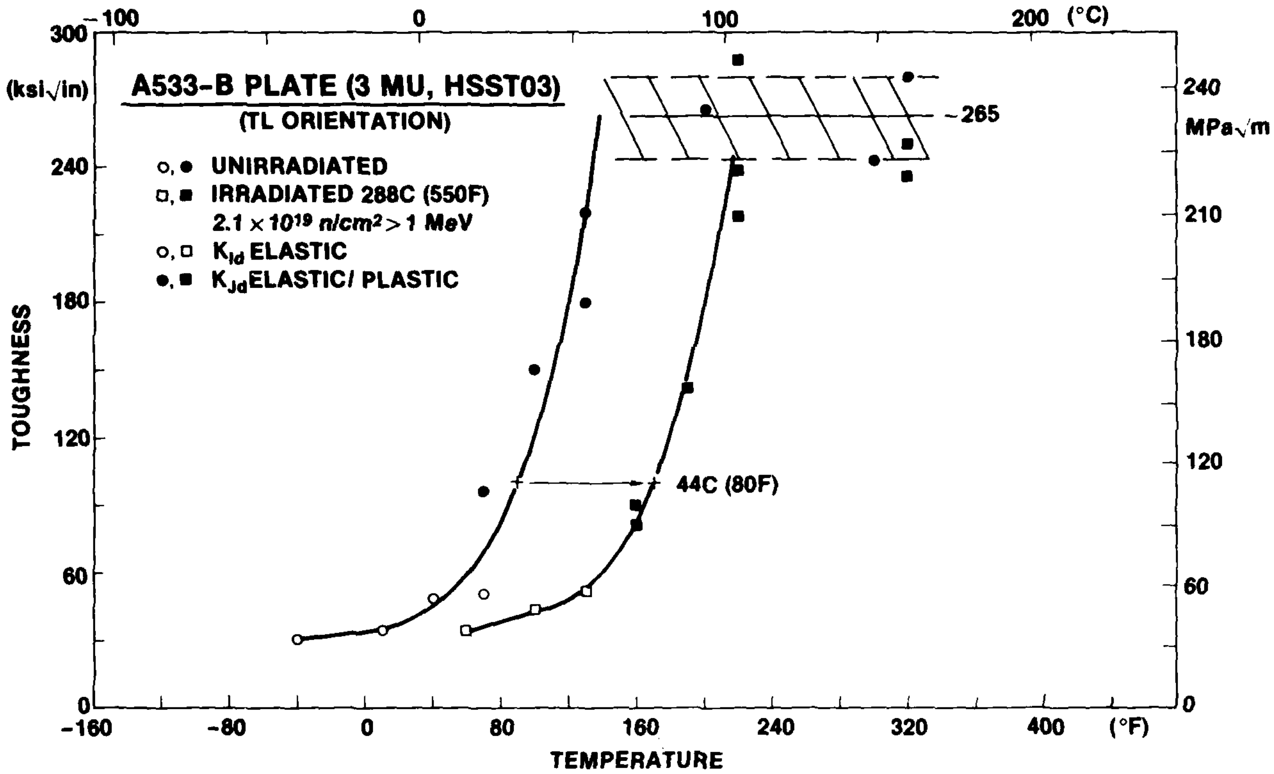


Fig. 18. Fracture toughness of the A533-B Class 1 reference plate (HSST Program Plate 03), Code 3 MU, supplied by the USA.

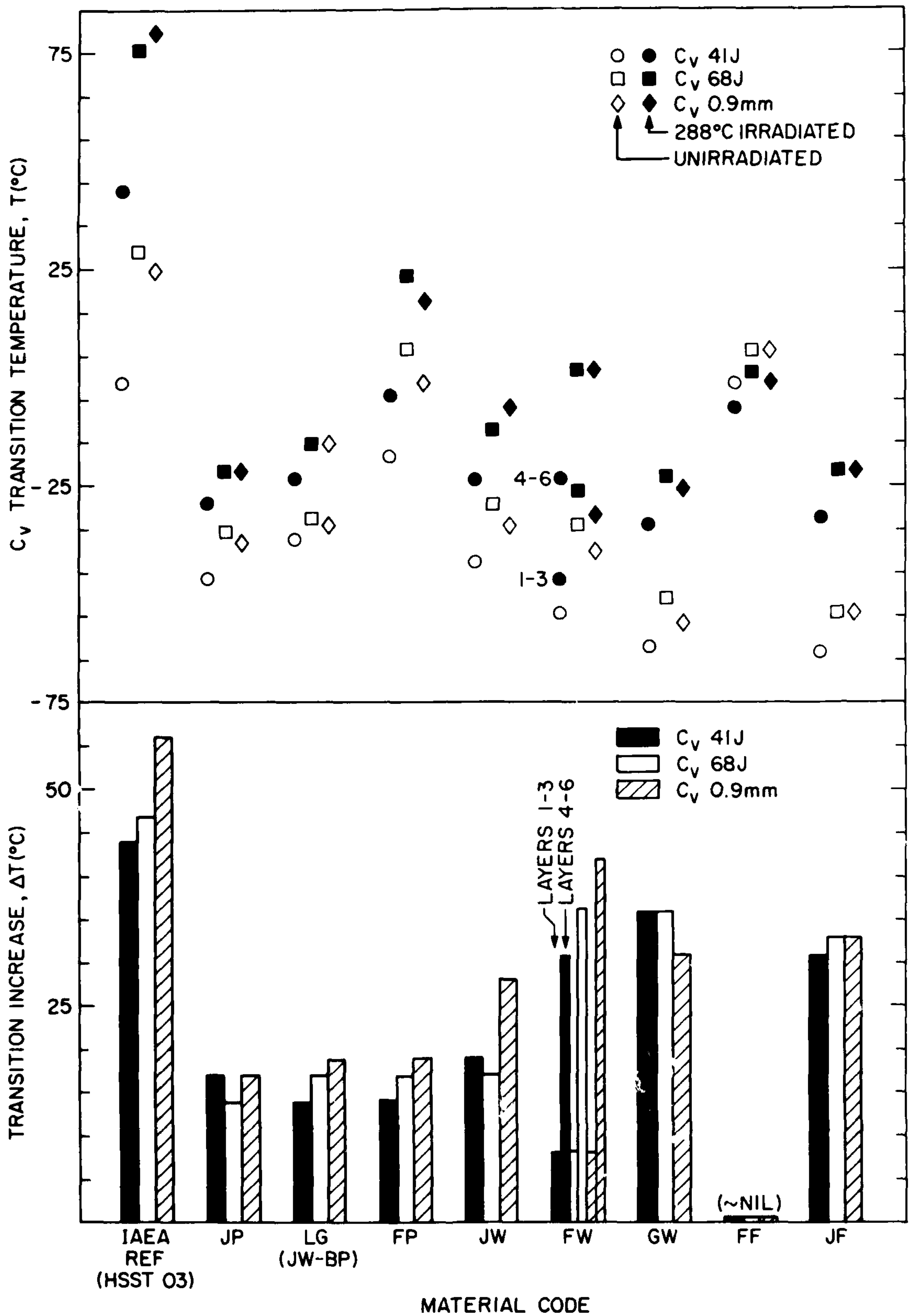


Fig. 19. Summary of $C_v$ 41J, 68J and 0.9 mm transition temperature determinations for unirradiated and irradiated conditions. The upper graph compares absolute transition temperatures. The lower graph compares transition temperature elevations by irradiation.

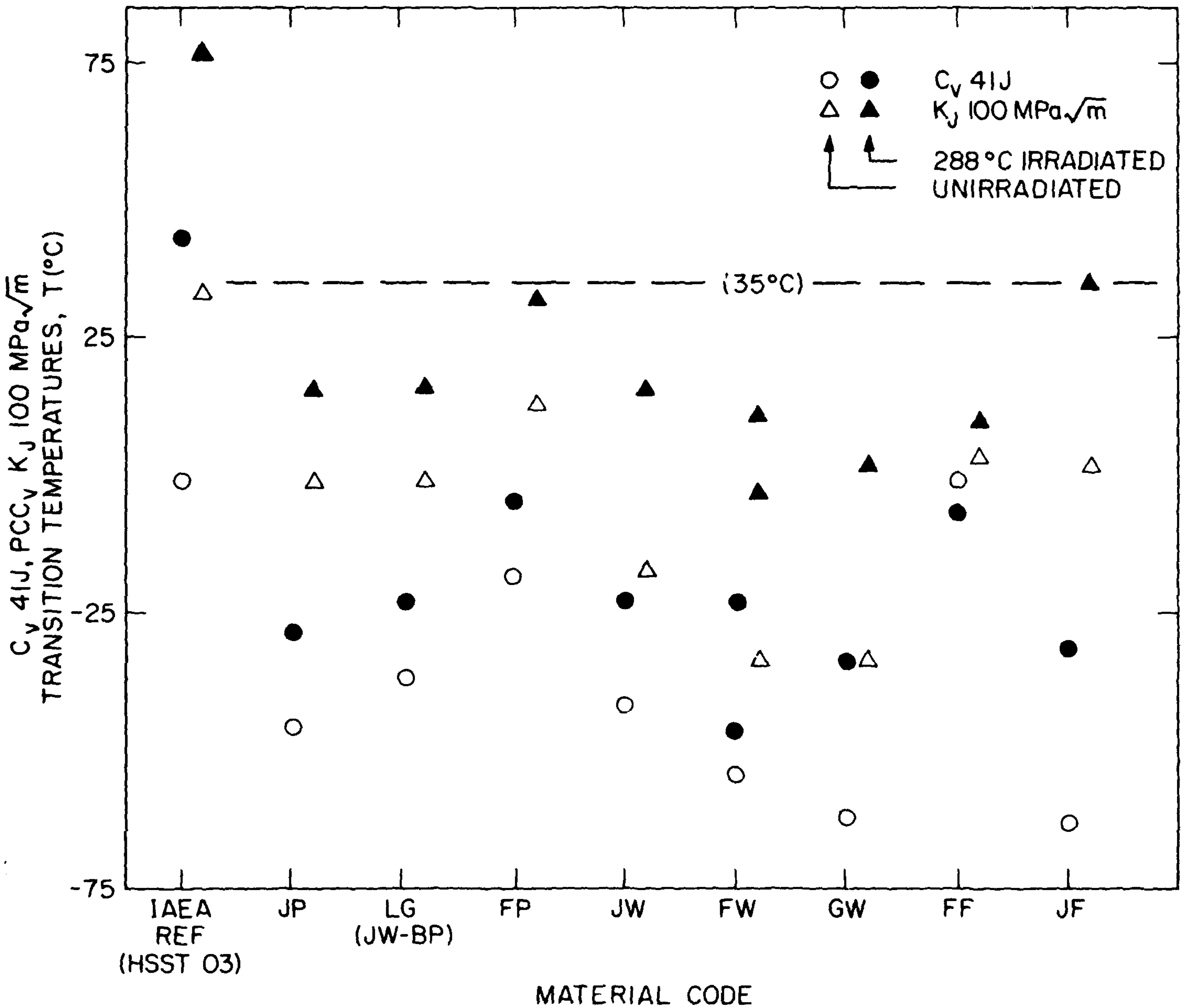


Fig. 20. Summary of 41J and $K_J$ 100 MPa$\sqrt{m}$ transition temperature determinations for unirradiated and irradiated conditions.

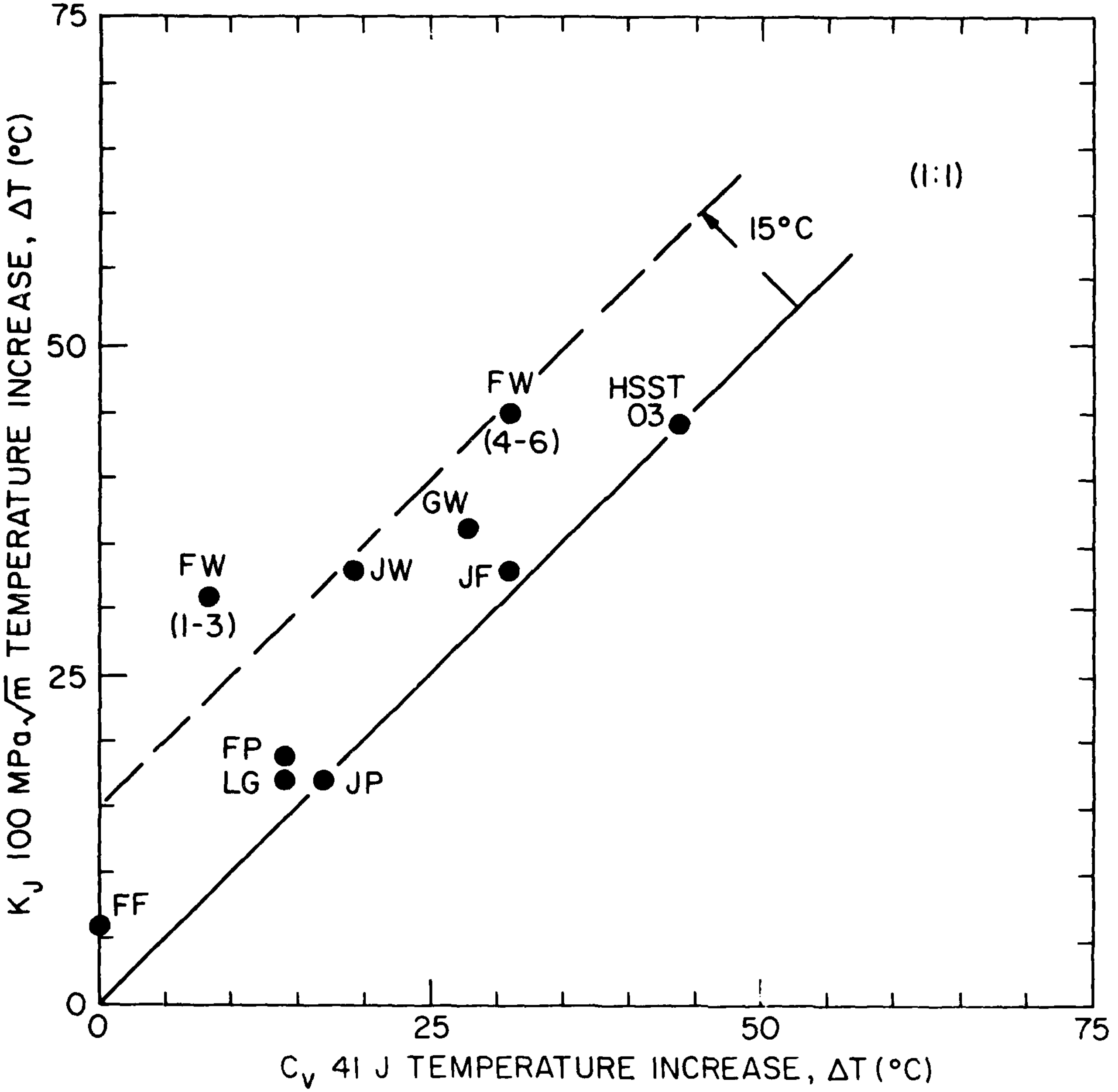


Fig. 21. Comparison of the $K_J$ 100 MPa $\sqrt{m}$ and 41J transition temperature elevations by 288°C irradiation. Agreement within 15°C is observed for all but one irradiation test (weld Code FW, layers 1-3). A small bias toward a greater $K_J$ 100 MPa$\sqrt{m}$ transition temperature elevation is indicated by the data scatter.

## DISCUSSION

The postirradiation determinations for the IWG-RRPC program materials by NRL have revealed high radiation resistance qualities and confirm the projected benefits of specifying low copper and low phosphorus impurity contents in reactor vessel steels. The findings compare well with prior determinations for USA-produced steels having similarly low impurity levels. The performance of steels from the present study and the trend performance of improved steels and welds representing USA-production [13] is illustrated in Fig. 22.

The key factor for improved radiation resistance at 288°C appears to be the minimization of copper content to low (≤0.10%Cu maximum) levels. Current ASTM and AWS specifications for nuclear grade steels specify maximum allowable copper contents of 0.10% and 0.08%, respectively. A possible interaction of nickel content with copper content in radiation sensitivity development has also been suggested. Nickel contents up to 1%Ni do not appear to influence radiation embrittlement sensitivity if copper content is low; however, certain data comparisons suggest that nickel can intensify the detrimental effect of a high copper content. Recent tests with laboratory melts of steel having statistical nickel and copper content variations have tentatively confirmed this suspect synergism [14].

## FUTURE RESEARCH DIRECTIONS

Radiation resistance assessments using larger fracture toughness specimens, such as the 25.4 mm thick compact tension specimen, would be valuable for confirmation of the trends reported here. The exposure of the materials to higher neutron fluences would also be beneficial and would permit additional comparisons with the USA-improved production steels. Future expansion of the IWG-RRPC program to include fatigue crack growth resistance tests of irradiated material in high temperature (288°C) water environments may also warrant consideration pending the outcome of tests now underway in the USA [15].

## CONCLUSIONS

The intent of the IWG-RRPC effort was to demonstrate that through careful specification and within current technology, reactor steels and welds can be produced routinely with high preirradiation fracture resistance qualities and with high radiation embrittlement resistance at vessel service temperatures. The results of the present investigation provide a positive response to both questions. In addition, the observations show good agreement between non-USA and USA-improved production

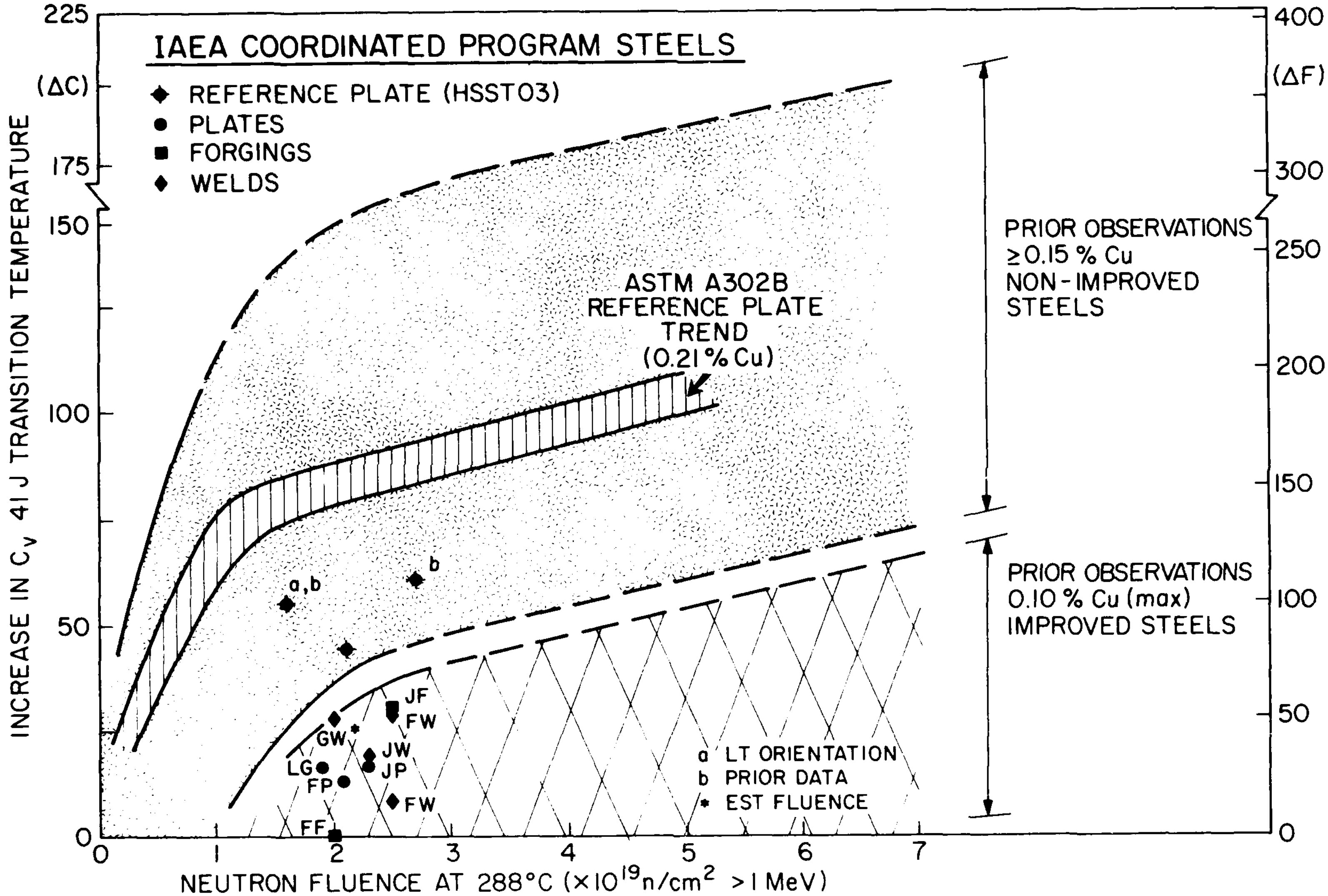


Fig. 22. Comparison of radiation resistance of steels and welds produced by the FRG, France and Japan (0.01 to 0.07%Cu) with the trend behavior of improved steels produced in the USA. Good agreement is found. Data for the reference plate (0.12%Cu) falls in the lower region of the data trend band for nonimproved (high copper) steels and welds.

materials in radiation resistance capabilities. The A533-B reference plate (HSST 03) by virtue of its 0.12%Cu content is not considered fully representative of current improved production material, and barely meets ASTM supplemental specifications on check analysis for reactor beltline material. Pending the outcome of the full IWG-RRPC program, it is tentatively concluded that the low copper, low phosphorus content steels and welds produced overseas can be evaluated within the same framework as USA-produced steels in the NRC Regulatory Guide 1.99.

A tentative correlation of $C_V$ 41J and $K_J$ 100 MPa$\sqrt{m}$ transition temperature elevations by irradiation was also established.

ACKNOWLEDGMENTS

This study was sponsored by the Reactor Safety Research Division, Metallurgy and Materials Branch, U. S. Nuclear Regulatory Commission.

REFERENCES

1. "Coordinated Research Programme on Analysis of the Behavior of Advanced Reactor Pressure Vessel Steels Under Neutron Irradiation," IWG RRPC-78/81, International Atomic Energy Agency, Vienna, Austria, 17-18 October 1977.

2. U. Potapovs and J. R. Hawthorne, "The Effect of Residual Elements on 550°F Irradiation Response of Selected Pressure Vessel Steels and Weldments," Nuclear Applications, Vol. 6(No. 1):27-46 (Jan 1969).

3. J. R. Hawthorne, "Demonstration of Improved Radiation Embrittlement Resistance of A533-B Steel Through Control of Selected Residual Elements," pp. 96-127 in Irradiation Effects on Structural Alloys for Nuclear Reactor Applications, ASTM STP 484, American Society for Testing and Materials, Philadelphia, Pa., 1971.

4. J. R. Hawthorne, "Radiation Resistant Weld Metal for Fabricating A533-B Nuclear Reactor Vessels," Welding Journal Res. Suppl. Vol. 51(No. 7):369s-375s (July 1972).

5. J. R. Hawthorne, E. Fortner, and S. P. Grant, "Radiation Resistant Experimental Weld Metals for Advanced Reactor Vessel Steels," Welding Journal Res. Suppl. Vol.49(No. 10):453s-460s (Oct 1970).

6. "Effects of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials," Regulatory Guide 1.99, Rev. 1, U. S. Nuclear Regulatory Commission, Office of Standards Development, Washington, D.C., April 1977.

7. "Standard Methods for Notched Bar Impact Testing of Metallic Materials," E23-72, Annual Book of ASTM Standards, Part 10, 1978, pp. 235-251, American Society for Testing and Materials, Philadelphia, Pa.

8. D. R. Ireland, W. L. Server, and R. A. Wullaert, "Procedures for Testing and Data Analysis, Task A - Topical Report," ETI Technical Report 75-43, Effects Technology, Inc., Santa Barbara, CA, pp. 5-1 to 5-52, Oct 1975.

9. E. P. Lippencott and P. A. Ombrellaro, "Buffalo Light Water Reactor Calculation," Letter Report to J. R. Hawthorne, Nov. 15, 1977.

10. Fracture Toughness and Surveillance Program Requirements, Appendices G and H, Title 10, Code of Federal Regulations, Part 50 (10 CFR Part 50), U. S. Atomic Energy Commission, Federal Register 45, No. 222, Nov. 14, 1980, pp. 75536-75539.

11. F. J. Loss, Editor, "Structural Integrity of Water Reactor Pressure Boundary Components, Quarterly Progress Report, April-June 1980," NUREG/CR-1783, NRL Memorandum Report 4400, Naval Research Laboratory, Washington, D.C., Feb. 20, 1981.

12. J. R. Hawthorne, "The NRL-EPRI Research Program (RP886-2), Evaluation and Prediction of Neutron Embrittlement in Reactor Pressure Vessel Materials, Annual Progress Report for CY 1970. Part 1. Dynamic $C_v$, $PCC_v$ Investigations," NRL Memorandum Report 4431, Naval Research Laboratory, Washington, D.C., Dec. 31, 1980.

13. J. R. Hawthorne, J. J. Koziol, and S. T. Byrne, "Evaluation of Commercial Production A533-B Steel Plates and Weld Deposits with Extra-Low Copper Content for Radiation Resistance," pp. 278-294 in Effects of Radiation on Structural Materials, ASTM STP 683, American Society for Testing and Materials, Philadelphia, PA., 1979.

14. J. R. Hawthorne, "Significance of Selected Residual Elements to the Radiation Sensitivity of A302-B Steel," presented to 1981 Annual Meeting of the American Nuclear Society, Miami, Florida, 11 June 1981 (to be published).

15. W. H. Cullen and F. J. Loss, "Interpretation of USA Results of Corrosion Fatigue of RPV Steels in Typical PWR Environnments," SMIRT-6 Post-Conference Seminar No. 8, "Assuring Structural Integrity of Steel Reactor Pressure Boundary Components," Paris, France, 24-25 Aug 1981 (to be published).

NRC FORM 335

U.S. NUCLEAR REGULATORY COMMISSION

**BIBLIOGRAPHIC DATA SHEET**

1 REPORT NUMBER (Assigned by DDC)
NUREG/CR-2487
NRL Memo Rpt 4655

4 TITLE AND SUBTITLE (Add Volume No., if appropriate)
Evaluation of IAEA Coordinated Program Steels and Welds for 288°C Radiation Embrittlement Resistance

2 (Leave blank)

3 RECIPIENT'S ACCESSION NO

7 AUTHOR(S)
J.R. Hawthorne

5 DATE REPORT COMPLETED
MONTH December YEAR 1981

9 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Naval Research Laboratory
Washington, DC 20375

DATE REPORT ISSUED
MONTH February YEAR 1982

6 (Leave blank)

8 (Leave blank)

12 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10 PROJECT TASK WORK UNIT NO

11 CONTRACT NO
NRC FIN B5528

13 TYPE OF REPORT

PERIOD COVERED (Inclusive dates)

15 SUPPLEMENTARY NOTES

14 (Leave blank)

16 ABSTRACT (200 words or less)


Eight steel materials supplied by the Federal Republic of Germany, France and Japan to the International Atomic Energy Agency (IAEA) Program on "Analysis of the Behavior of Advanced Reactor Pressure Vessel Steels Under Neutron Irradiation" were irradiated at 288°C for assessments of relative notch ductility and dynamic fracture toughness change with $\sim 2 \times 10^{19}$ n/cm$^2$, E >1 MeV. Notch ductility and fracture toughness were determined, respectively, by Charpy-V and fatigue precracked Charpy-V test methods. An A533-B steel plate (HSST 03) produced in the USA was included in the irradiation test series for reference.

The materials (plate, weld, forging) were found to be generally more resistant to radiation-induced embrittlement than the reference material. Observed dissimilarities in radiation sensitivity are attributed to copper content differences between the eight materials (0.01 to 0.07 percent copper range) and the reference plate (0.12 percent copper). Radiation resistances, however, correspond well with the trend of radiation resistance reported for USA-produced steels and welds having similar copper and phosphorus contents.

A general correlation of transition temperature elevations measured independently by the Charpy-V and the precracked Charpy-V test methods was observed.


17 KEY WORDS AND DOCUMENT ANALYSIS

17a DESCRIPTORS

17b IDENTIFIERS OPEN ENDED TERMS

18 AVAILABILITY STATEMENT
Unlimited

19 SECURITY CLASS (This report)
Unclassified

20 SECURITY CLASS (This page)
Unclassified

21 NO OF PAGES

22 PRICE
$

NRC FORM 335

FILMED

9-82